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The digital footprint of the cycling city GPS cycle routes visualization and analysis

(La huella digital de la ciudad ciclista: visualización y análisis de rutas ciclistas GPS)

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PRESENTADA POR

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Doctoral dissertation

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A mi abuela Ángeles,
ese árbol, ya centenario,
de amor y sabiduría.

To my grandmother Ángeles,
that centerary tree
of love and wise.

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Contents

Abstract / Resumen

Abstract

"*The bicycle is a curious vehicle. Its passenger is its engine*"

John Howard (1987)

This famous quote by the American cyclist John Howard (1987) highlights an important fact for this thesis: cycling mobility is extraordinarily complex because the human engines that the quote refers to are affected by a wide range of physical, social, environmental and psychological factors. This is the reason why cycling mobility is being currently analysed from multiple perspectives by researchers from many different disciplines. In addition, the fact that research production on cycling mobility has grown exponentially over the last years, also evidences the extraordinary interests of this field of research.

However, there are some relevant aspects of cycling mobility that still remain relatively underexplored, such as its spatial dimension, which is the main focus of interest of this research. This thesis essentially explores cycling mobility across the city, and its main objective is to collect, visualise, analyse and model cyclists' routes and the distribution of cycling flow across the urban street-network, with the aim of reaching a better understanding of cyclists' behaviour and cycling mobility patterns in cities. The research also aimed at analysing cyclists' operating speeds, estimating cycling travel times and performing a comparative analysis of cycling accessibility in relation to other transport modes. Finally, it aimed at predicting the values of cycling travel times and cycling accessibility for future scenarios, derived from the implementation of specific policies or the construction of particular infrastructure.

The thesis is focussed on the analysis of the city of Madrid, as a case study, and, in order to provide an overall understanding of cycling mobility, it includes the analysis of three different types of cyclists: casual cyclists, bike messengers and BiciMAD (Madrid Bike Share System) users. The analysis of casual cyclists and bike messengers is based on the study of the GPS routes collected through the *Madrid Cycle Track* initiative (www.huellaciclistademadrid.es), an online platform launched in the context of this thesis, with the aim of capturing cycling routes and other information from volunteer cyclists and messengers. This initiative illustrated, for the first time, the real flow of casual cyclists and bike messengers in Madrid, through a number of online maps embedded on the digital platform, representing different aspects of cycling mobility, such cyclists' routes according to the purpose of the journey.

The analysis of the cycling flow derived from the Madrid Bike Share System (BiciMAD) activity is based on the study of a sample of over 250,000 GPS routes registered by the system in April 2017. The results show how this flow is distributed across the urban street-network, at different moments, and the study uncovers the diverse levels of cycling activity over the course of the day, and during the weekdays, weekends or holidays, as well as the different cycling patterns of frequent and occasional users.

The results obtained from the analysis of cyclists' operating speeds and travel times, as well as the from the comparative analysis of cycling accessibility in relation to other transport modes, support John Howards' declaration, and present cycling as a particular transport mode, sensitive to many elements. The models performed shed light on the influence of a wide range of factors on cyclists' speed, quantifying the specific impact of a wide range of variables of a different nature: from the street-network properties (such as slope, motor traffic speed or density of traffic lights and intersections) to other properties related to the trip (such as the purpose of the journey) or the cyclist (such as gender or age). These models also allow us to estimate cyclists' travel times for the entire street network and not only in the street-network arcs where we have cyclists' records (just 30% of the total) and, furthermore, they also allow us to predict cyclists' travel times and accessibility in future scenarios, given certain changes in the network, such as the execution of new infrastructure or implementation policies, such as slowing down traffic speed. In consequence, the models can be considered as tools that may help decision makers when evaluating future scenarios.

Finally, models' accurate estimation of cyclists' travel times also allowed us to conduct a comparative analysis of accessibility, and evaluate competitiveness between different transport modes (private car, public transport, cycling, bicycle sharing systems and pedestrian mobility), considering mobility during the morning peak hour of a working day. The results showed that cycling is the most competitive transport mode for small-medium distances (under 21 minutes in length for Madrid), which is a relevant finding not only for casual cycling mobility, but also for bike-driven parcel delivery service, since bike-messenger performance is even greater than casual cyclists'. Therefore, this thesis also aims at raising awareness of cycling, not only as an environmentally-sustainable transport mode, but also as the most efficient mode for an important range of distances.

Resumen

"La bicicleta es un vehículo curioso. El pasajero es su motor"

John Howard (1987)

El ciclista americano John Howard (1987) subraya en esta cita un hecho fundamental en el planteamiento de esta tesis: la movilidad ciclista es extraordinariamente compleja, debido a que estos motores humanos, a los que la cita hacer referencia, son sensibles a una gran variedad de factores físicos, sociales, medioambientales y psicológicos. Este es el motivo por el que la movilidad ciclista está siendo actualmente estudiada desde muy distintas perspectivas por investigadores de diversas disciplinas. Por otro lado, el hecho de que la producción de investigación enfocada en su estudio haya crecido de manera exponencial en los últimos años, evidencia también el extraordinario interés de este campo de investigación.

Sin embargo, aún hay algunos aspectos relevantes de la movilidad ciclistas que aún permanecen relativamente inexplorados, como su dimensión espacial, la cual constituye el interés principal de esta investigación. En esencia, esta tesis explora la movilidad ciclista en las ciudades, y su objetivo principal es visualizar, analizar y modelizar las rutas que siguen los ciclistas, así como la distribución del flujo ciclista sobre las distintas calles que constituyen la trama urbana, con el ánimo de llegar a un mejor entendimiento del comportamiento ciclista y de los patrones de la movilidad ciclista en las ciudades. La investigación analiza las velocidades de circulación de los ciclistas, estimando a partir de ellas sus tiempos de viaje y desarrollando un análisis de accesibilidad comparativo entre distintos modos de transporte. Finalmente, los modelos desarrollados permiten también predecir los tiempos de viaje y la accesibilidad ciclista para futuros escenarios, correspondientes a la posible o potencial implementación de políticas específicas o la construcción de determinadas infraestructuras ciclistas.

Esta tesis toma como caso de estudio la ciudad Madrid y, de cara a contribuir a un entendimiento de la movilidad ciclista lo más amplio posible, incluye el análisis de tres colectivos ciclistas: los ciclistas urbanos normales, los bici-mensajeros y los usuarios de BiciMAD, el Sistema de Bicicleta Pública de la ciudad de Madrid. El estudio de los ciclistas urbanos normales y de los bici-mensajeros se basa en el análisis de las rutas GPS recopiladas a través de la iniciativa Huella Ciclista de Madrid (www.huellaciclistademadrid.es), una plataforma digital lanzada en el contexto de esta tesis con el objetivo de capturar rutas ciclistas y otra información complementaria proveniente de voluntarios ciclistas y bici-mensajeros. La iniciativa recopiló más de 6,000 rutas que suman alrededor de 48,000 km de recorridos ciclistas, y representó, por primera vez, el flujo ciclista real de los mencionados colectivos ciclistas a través de una serie de mapas online, embebidos en la plataforma digital, que ilustran distintos aspectos, como las rutas individuales de acuerdo al motivo del viaje.

El estudio del flujo ciclista derivado de la actividad de BiciMAD se basa en el análisis de una muestra de más de 250,000 rutas GPS, registradas por el sistema durante el mes de abril de 2017. Los resultados muestran cómo el flujo ciclista se distribuye a través de la trama urbana en diferentes

momentos, representando y analizando los diferentes niveles de actividad ciclista a lo largo del día, durante el fin de semana, entre semana o en vacaciones (Semana Santa). La investigación estudia también las diferentes pautas de movilidad de los usuarios frecuentes y ocasionales, en cuanto a la edad como en relación con la duración, distancia y velocidad media de viaje, así como evolución de estas variables en distintos momentos del día o según el tipo de día.

Los resultados obtenidos a partir del análisis de las velocidades de circulación y tiempos de viaje de los ciclistas, así como a partir del análisis comparativo de accesibilidad ciclista en relación a distintos modos de transporte, apoyan la afirmación de John Howard y presentan la movilidad ciclista como un tipo de movilidad sensible a múltiples factores. Los modelos aplicados arrojan luz sobre la influencia de estos factores sobre la velocidad ciclista, cuantificando el impacto específico de variables de muy distinta naturaleza: desde propiedades de la red (como la pendiente de la vía, la velocidad e intensidad del tráfico o la densidad de semáforos e intersecciones), hasta propiedades relativas al viaje (como el motivo del mismo) o relacionadas con el propio ciclista (como el género o la edad). Los modelos también nos permiten estimar los tiempos medios de viaje en bicicleta para toda la red y no solo para aquellos tramos en los que se ha encontrado flujo ciclista, permitiendo además estimar estos tiempos de viaje ciclista, y la accesibilidad derivada de ellos, en posibles escenarios futuros, dados ciertos cambios en la red, como la ejecución de nueva infraestructura ciclista o la implementación de medidas o políticas, como la reducción de la velocidad del tráfico rodado. Como consecuencia, estos modelos pueden ser considerados como herramientas que pueden ayudar a los tomadores de decisiones, de cara a evaluar las posibles políticas e infraestructuras a promover y desarrollar.

Finalmente, la posible estimación de los tiempos medios de viaje en bicicleta a partir de los modelos nos permitió realizar un análisis de accesibilidad comparativo considerando distintos modos de transporte (vehículo privado, transporte público existente en su conjunto, bicicleta, bicicleta pública y movilidad peatonal) y evaluar así la competitividad de los mismos para distintos tiempos de viaje, tomando como origen un punto céntrico de la ciudad de Madrid y como momento del día el de hora punta de la mañana. Los resultados obtenidos muestran que la bicicleta es el modo de transporte más competitivo para pequeñas y medias distancias (por debajo de 21 minutos de duración de viaje), lo cual es un resultado muy relevante, no sólo en relación a la movilidad de los ciclistas normales sino también en cuanto a las compañías de bici-mensajería, cuyos tiempos de viajes son además menores que los de los primeros. Como consecuencia de estos resultados, el último objetivo de esta tesis es crear conciencia acerca de la movilidad ciclista, no sólo como un modo de transporte sostenible, sino realmente competitivo, para un número considerable de viajes urbanos.

1 Introduction

1.1 Relevance of the topic

With the aim of shifting towards a more sustainable urban transport model, cycling mobility is being promoted in many cities. In consequence, over the past years, a relevant number or studies have focussed on cycling mobility from multiple perspectives. However, there are some relevant aspects that still remain relatively underexplored, such as the spatial dimension of cycling mobility, which is the main focus of interest of this research. More specifically, this thesis essentially explores cycling mobility across the city. It collects information about the paths that cyclists use to follow, visualizing and analysing cyclists' routes according to a wide range of factors, with the aim of recognising cyclists' travel patterns. It identifies the most important streets in terms of cycling flow, it calculates cyclists' travel distances, travel times, operating speeds, it analyses the impact of different factors on these operating speeds (such as the slope, the presence of traffic lights of the intensity of motor traffic), estimates cycling urban accessibility and competitiveness in relation to other transport modes, among other questions that we will analyse in detail throughout the text.

For a long time, all these aspects had been poorly analysed by studies based on different kinds of surveys, essentially Stated and Revealed Preference methods, with important limitations as we will discuss later on. However, in recent years, the emergence of new location-based data has brought the opportunity to explore, for the first time, the spatial activity of cyclists with an unprecedented level of detail, and to perform more complex spatial analyses.

Recent investigations have studied basically two different types of location data: point or journey data, captured by the growing Bike Share Systems spread around the world (Etienne & Latifa, 2012; Froehlich, Neumann, & Oliver, 2009; O'Brien, Cheshire, & Batty, 2013; Zaltz Austwick, O'Brien, Strano, & Viana, 2013b) and GPS tracking data collected through smartphones applications or specific devices, gathered specifically with research purposes or made available by "Big App" Companies for research or planning (Broach, Dill, & Gliebe, 2011; Harvey & Krizek, 2007; Menghini, Carrasco, Axhausen, & Schüssler, 2010). This research is based on the analysis of these two different kinds of location data. Focussing on the analysis of Madrid as a case study, this thesis analyse data collected through the Madrid Bike Share System (BiciMAD) and also data collected through a specific initiative designed and developed with the purpose of collecting GPS routes from volunteer cyclists (crystalized in the digital platform www.huellaciclistademadrid.es). By doing so, this research actually covers the study of three different types of cyclists: casual cyclists, BiciMAD (Madrid Bike Share System) users and bike messengers from four different companies. The three groups had to be included in order to provide an overall picture of the existing cycling mobility, given their growing activity and presence in the area of study. The three groups will be analysed independently in order to identify potential differences in their corresponding mobility patterns.

Understanding the spatial dimension of cycling mobility, and exploring all the aspects previously considered is crucial in the current context. Today, cities and institutions are investing important resources with the aim of promoting cycling mobility, essentially by building cycling infrastructures – different types of bike lanes, parking facilities, special infrastructure at road junctions, etc. – by implementing a wide range of policies –to limit motor vehicles' speed, to reduce traffic volume, to educate new cyclists, to introduce economic incentives for the use of bike in companies or institutions, etc. – (Oldenziel & Albert de la Bruhèze, 2011) and by fostering the implementation of Bike Share Systems (BSS), programmes that have gained popularity and have grown exponentially over the past 10 years, in general, worldwide (Fishman, Washington, & Haworth, 2013), and particularly, in Spain (Anaya & Castro, 2011).

Analysing cycling mobility spatially is crucial in order to design efficient policies and implement useful infrastructure, where they are really needed. The analysis of cycling flow in certain streets may allow as to evaluate the impact of the implementation of certain policy or the construction of certain infrastructure or facility. In consequence, it also allows us to calibrate models and then predict what would be the effects of future investments and estimate the cycling flow derived from future scenarios.

In addition, especially relevant for policy makers may be the possibility of performing a more dynamic analysis of cycling activity. In this research, we examine cycling flow over the course of the day or at different periods of time or specific dates, and analyse the way in which certain mobility patterns evolve over time. This dynamic analysis is especially helpful, considering that the adoption of temporal measures and policies, such as the pedestrianization of certain urban areas during weekends, Sundays, specific holidays or at different moments of the day, or the opening of temporary bike lanes, are getting more and more popular in many cities worldwide. These dynamic analyses may provide relevant information and serve as the basis of dynamic proposals, offering different scenarios over time.

1.2 Research questions and objectives

1.2.1 Research questions

The previous introduction to the main focus of the thesis already anticipated some of the most relevant aspects that we wanted to explore throughout this research. The most important research questions that we aimed to address are described next.

RQ1. What is the relevance of analysing the spatial dimension of cycling mobility and, more specifically, cyclists' routes and cycling flow across the city?

Studying this spatial dimension of cycling mobility, and exploring cycling flow across the city might be crucial in order to understand cyclist's behaviour and the use that cyclists make of the city, especially on the use of certain urban streets and infrastructure. We will see if the results support some intuitive ideas ('cyclists' flow concentration in streets equipped with cycling infrastructure', for instance) or if, on the contrary, contradict some popular beliefs ('cyclists avoid roads with high levels of traffic', or 'e-bikers' speeds are much higher than regular bikers' speeds', for instance). Throughout this thesis, we will explore if our work based on the GPS tracks and other collected information allow us to answer these and other questions, since these answers are key in order to know what factors are having a greater impact on cyclists' route choice, or cyclists' speed, or safety, an in consequence, they are essential when planning and designing policies and infrastructure with the aim of promoting cycling mobility.

RQ2. What is the current understanding of the spatial dimension of cycling mobility?

Although urban cycling mobility has been growing in many cities all around the world (Oldenziel & Albert de la Bruhèze, 2011) and, over the past years, a relevant number of studies have analyses cycling mobility, we know very little about the way cyclists move around in cities. A similar lack of knowledge is found in the particular case of Bike Share Systems (BSS), which have grown exponentially over the past 10 years worldwide (Fishman et al., 2013), and particularly, in Spain (Anaya & Castro, 2011). We do not know how BSS cycling flow is distributed across the city, we actually know almost nothing about BSS cycling activity beyond the station level.

RQ3. What are the new research opportunities that new data sources on cycling mobility are offering?

The reason why the spatial dimension of cycling mobility had not been properly explored yet has not been a lack of interest, but the almost inexistence of data that could support this kind of analysis. The data available used to correspond to a number of counts in certain streets (manual counts of the number of cyclists at specific points in a precise date), or to Stated and Revealed Preference methods, that eventually could offer a very limited number of routes designed by volunteer cyclists on a map.

However, over the past 10 years, the availability of new datasets has led to an explosion on data-driven research in many fields, and cycling mobility is not an exception. New datasets have become widely accessible, capturing in detail processes that previously were estimated, under sampled, kept private, or simply poorly understood. The collection of GPS routes, through specific initiatives or through important App companies, or the data registered by the growing Bike Share Systems, are bringing the possibility of exploring the activity of cyclists with an unprecedented level of detail.

RQ4. What paths do cyclists follow? What are the most important urban arteries in terms of cycling flow? How is cycling flow distributed across the urban street-network? How can we measure this flow distribution?

The study of cyclists' real routes is relevant at two different levels. First, at the individual level, it is important to know what paths cyclists use to follow, what is their route choice and what are the factors that have a greater impact in their journey. Only by exploring individual routes and choices, we will understand cycling behaviour and its consequences and implications at the urban scale.

The second level of interest is the consideration of cycling flow at the urban scale, in other words, the exploration of the collective cycling track on the urban street network. To analyse how cycling flow is distributed across this network is fundamental in order to identify the most important axes in terms of cycling flow. This analysis provides fundamental information for the planning and designing of cycling infrastructure, or for the implementation of local policies or measures, where they are really needed, according to the existing demand, made visible through cycling flow maps.

RQ5. What are the mobility patterns of the different groups of cyclists –casual cyclists, bike messengers and BSS users–?

In order to provide an overall view of cycling mobility in the area of study, we have considered in this research, three different groups of cyclists: casual cyclists, bike messengers and BiciMAD (Madrid Bike

Share System) users. The activity of the three groups have been increasing over the last years. While twenty years ago, there was only one bike-messenger company operating in the city of Madrid, now the figure has gone up to dozens, some of which are incorporating hundreds of new riders, such as *Deliveroo* or *Glovo*. In the case of BiciMAD, the activity has been increasing since it was launched, in mid-2014, comprising 1,560 bikes and 123 docking stations, to the present, when the system is operating with 2,028 bikes and 172 stations, and with approximately an average number of 8 thousand trips per day.

Our initial hypothesis is that the three groups, present some remarkable differences in their mobility patterns, since they cycle with different purposes and respond to diverse profiles. We also consider that it is necessary to analyse the three groups independently, so that we can promote specific measures, policies or infrastructure that may result effective for each group.

RQ6. What is the impact that different urban conditions, cycling infrastructure or variables related to the journey or to the cyclists, have on cycling mobility? How all the factors affecting cyclists shape their mobility patterns?

Cyclist behaviour is complex and not easily predictable because it is influenced by a diverse set of factors. Cyclists of different gender or age, may show different patterns, but also the purpose of the journey is relevant, since the routes chosen or the circulating speed may be different when cycling for commuting purpose than for leisure or sport. Urban conditions have also to be analysed, since cycling mobility may be dramatically affected by factors such as motor traffic intensity or speed, or by the slope of the streets or the presence or absence of bike infrastructure, for instance. Even the weather conditions may affect cycling behaviour.

RQ7. How do cycling mobility patterns evolve over time?

Until recently, conventional data sources provided information of cycling mobility for a specific date and time, a static view that could only produce static analyses on whatever aspect we wanted to analyse. However, the availability of new data sources has recently opened the opportunity to perform more dynamic analyses, based on data with high temporal resolution and constantly updated. This fact allows us to study the evolution of the cycling activity over the course of a day, or to identify the potential different patterns of cycling mobility in different periods of time or at different dates of the year.

RQ8. What are the factors that have a greater impact on cyclists' operating speeds and travel times?

Similarly, there are a wide range of factors that may influence cyclists' operating speeds and, in consequence, travel times. The speed at a particular street segment may be determined by factors such as the number of junctions, the number of traffic lights, the slope of the street, the existence of certain bike infrastructure, the speed and intensity of motor traffic, etc. In addition, individual factors such as gender or age, or others, such as the purpose of the journey, may influence cycling speeds.

To analyse the impact of all these factors on cycling speeds is crucial in order to develop more accurate models of cycling travel times and, in consequence, in order to perform accessibility analyses, for instance.

RQ9. Is cycling a competitive transport mode in terms of accessibility?

We all agree that cycling is a sustainable transport mode, the most sustainable transport mode after walking. We also know about the different social, economic and environmental benefits of promoting cycling in cities. But, is cycling also a competitive transport mode? Very little studied have focussed on analysing how cycling can compete with other transport mode in terms of the accessibility that it provides.

Taking advantage of the analysis of cyclists' speeds and the accurate estimation of cyclist' travel times, we consider that it is important to raise this question and evaluate cycling travel times and accessibility in relation to the one provided by other transport modes in cities. Our hypothesis in this sense is that cycling may constitute a competitive transport mode for an important number of journeys, between certain travel distances. We also think that it may be more competitive especially in periods of time in which other transport modes are less competitive, such as private car during the morning peak.

1.2.2 Main research goal, and general and specific objectives

1.2.2.1 Main research goal and general objectives

The main research goal of this thesis is, essentially, to study urban cycling flow. Cycling flow in cities do not respond to a top-down planning (as it happens with other public transport modes), so we have followed a bottom-up approach in order to explore cycling flow, in a similar way as cities are studied as complex systems, which general dynamics are the result of millions of individual decisions and interactions. Because of this, first, we had focus on the analysis of cyclists and then, we could focus on the analysis of the cycling city, as Figure 1.1 illustrates. The focus on cyclists and the focus on the city opened two parallel research lines, each of them leading to different but related research objectives, which are illustrated in Figure 1.1.

In summary, the general objectives of this thesis are to visualise, analyse and model cyclists' routes and the distribution of cycling flow across the urban street-network. The research also aims at analysing cyclists' operating speeds, estimating cycling travel times and performing a comparative analysis of cycling accessibility in relation to other transport modes. Finally, it aims at predicting cycling travel times and cycling accessibility for future scenarios, derived from the implementation of specific policies or the construction of particular infrastructure.

The research is focussed on the analysis of the city of Madrid, as a case study, and in order to provide an overall understanding of cycling mobility, it includes the analysis of three different types of cyclists: casual cyclists, bike messengers and BiciMAD (Madrid Bike Share System) users.

1.2.2.2 Specific objectives

The specific objectives are closely related to the research questions raised in the previous section, as it is illustrated on Figure 1.2. These specific objectives are:

OB1. To establish a theoretical framework for the thesis.

Firstly, it is important to review the existing literature on the spatial analysis of cycling mobility and the study of cyclists' routes and travel patterns. Secondly, it becomes crucial also to perform an up to date exploration of the new data sources that that are becoming increasingly accessible to researchers and policy makers, and then, to study the emergent research studies based on these new data, most of which have been conducted over the last ten years. Finally, it is essential to learn the new techniques applied to the data available, to identify the main achievements as well as the main failures, and become aware of the most important limitations of the new data sources.

OB2. To define a strategy with the aim of collecting cyclists' routes and to develop a methodology oriented to clean, process and analyse the collected data.

This thesis is necessarily based on the analysis of real cyclists' routes. However, at the moment in which this research started, there were no data available for the selected case study, the city of Madrid. Only recently, in mid-2017, the Municipal Transport Enterprise (EMT) started to make public some GPS tracks related to the BiciMAD activity. The only data available regarding casual cyclists were different surveys and specific counts of cycling volumes at specific locations in particular dates.

Because of this, it was necessary to define, as one of the firsts objectives, a strategy aimed at collecting cyclists' routes in the city of Madrid. Eventually, we set the specific objective of launching an initiative, named *Huella Ciclista de Madrid* (Madrid Cycle Track), which essentially would consist on a digital platform that allowed us to collect thousands of routes from volunteer cyclists. The initiative and the platform will be described in detail later on.

Finally, another objective was to clean and process the collected data, by applying specific techniques to the GPS raw tracks collected through the Madrid Cycle Track initiative or coming from the BiciMAD recorded data.

OB3. To estimate, visualize and analyse the distribution of cycling flow across the urban street-network.

Once the data was cleaned and processed, the next objective was to estimate the distribution of cycling flow across the urban street-network, and to visualize it in order to provide and overall understanding of how this flow is distributed, allowing us to easily identify the most important arteries in terms of cycling flow.

OB4. To explore the mobility patterns of the different groups of cyclists: casual cyclists, bike messengers and Public Bike Share users.

With the aim of providing an overall understanding of cycling mobility in the area of study, in this research we have considered the three most important groups of cyclists in Madrid: casual cyclists, bike messengers and BSS users. Casual cyclists' and bike messengers' routes were collected through the Madrid Cycle Track initiative. BiciMAD routes were provided by the Municipal Transport Enterprise (EMT). The objective was to analyse the three types of mobility independently, although under a common research methodology, with the aim of being able to perform a comparative analysis and offer comparable results.

OB5. To identify and analyse cycling mobility patterns according to a wide range of variables.

This thesis analyses cycling mobility according to the impact of factors of three different natures. First, it considers characteristics of cyclists, with variables such as gender or age. The second kind of factors are the properties or conditions of the urban street network, which includes slope, motor traffic volume and speed, the existence or absence of any kind of cycling infrastructure, etc. Finally, it also analyses different variables related to the journey, such as the purpose of the journey (commuting, leisure, sport, study, errands, shopping, etc.), the length of the trip, the accumulated high elevation

OB6. To perform a dynamic visualization and analysis of cycling mobility patterns over time.

The availability of new data sources provides the opportunity of exploring mobility patterns in a dynamic way. First, we aim at analysing cycling flow over the course of a day or according to different periods of time. The objective is to compare the different use of the city and the street network through different maps, reflecting the different scenarios, but also through different video-visualisations, that will illustrate cyclists flow in a more dynamic way. Secondly, we aim at studying the variation of mobility patterns over time, such as cyclists' speeds and travel times, travel distances or cycling accessibility.

OB7. To analyse and model cycling speeds according to the impact of a wide range of factors.

Regarding the analysis of cycling speeds, other variables must be considered in addition to the previously listed. The number of street junctions and, especially, the number of traffic lights, found in a street segment, the type of bicycle, the time of the day or even weather conditions, may affect significantly cyclists' operating speeds and, in consequences, cycling travel times.

OB8. To analyse cycling accessibility and to conduct a comparative analysis different transport modes, evaluating the competitiveness between them.

Once we can estimate cyclists' operating speeds with relatively accuracy, it is possible to predict cyclists' travel times and, in consequence, to perform different kinds of analyses of accessibility. The first objective is to estimate the isochrones that correspond to different of travel times according to different transport modes, and therefore provide a comparative analysis of accessibility, for the same urban area at the same time of the same day of the week. The different transport modes to consider will be walking, private car, public transport (including train, underground and bus) and, of course, cycling.

The second objective will be to perform an analysis of the accessibility provided by BiciMAD, according to the average travel times estimated for different periods of time. In this case, the extension of the analysis will be constraint to the area covered by the BSS.

Figure 1.1: Relationship between main research goal and general research objectives

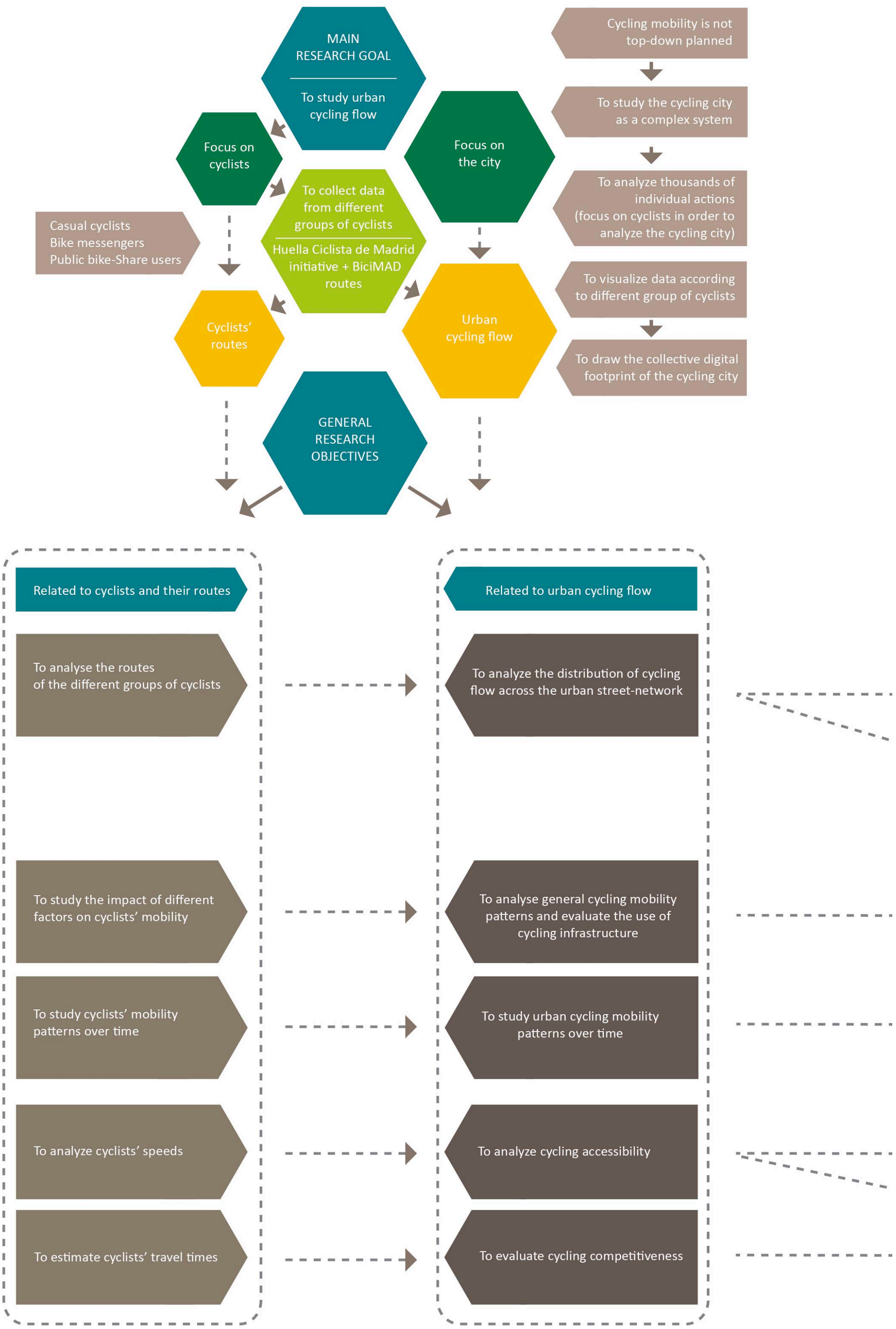
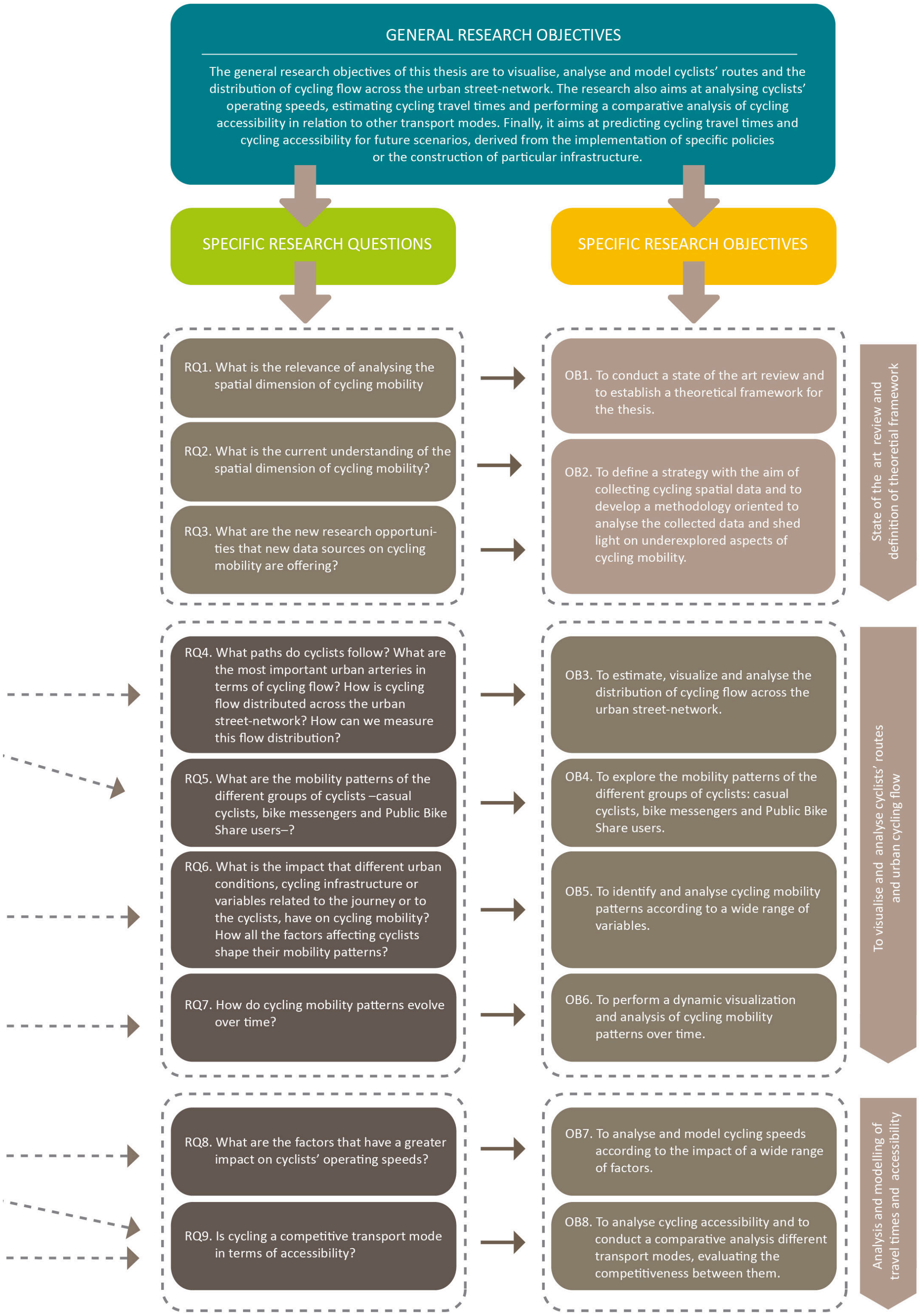


Figure 1.2: Relationship between research questions and specific research objectives



1.3 Thesis structure and summary of the content

This thesis is structured in seven sections. The first section introduces the research, underlining the relevance of the topic addressed. It presents the main goal and the specific objectives defined in order to respond a number of research questions also included in the section. Finally, it describes the structure of the thesis and how the different objectives have been address throughout the research.

The second section introduces the research within a theoretical framework, by providing a background based on an extensive review of the existing literature. First, it describes current approaches related to the study of cycling mobility. Then, it provides an exhaustive review of the data sources and the associated new research opportunities, based on the review paper entitled "*Big Data and Cycling"* (Romanillos, Zaltz Austwick, Ettema, & De Kruijf, 2016), a research developed within the context of this thesis and published in the journal *Transport Reviews*. The text reviews the techniques, objectives and findings of a growing number of studies that we classified into three groups according to the nature of the data they are based on: GPS data (spatio-temporal data collected using the global positioning system (GPS)), live point data and journey data. We discuss the movement from small-scale GPS studies to the 'Big GPS' data sets held by fitness and leisure apps or specific cycling initiatives, the impact of Bike Share Programmes (BSP) on the availability of timely point data and the potential of historical journey data for trend analysis and pattern recognition. Finally, the section reviews current practices regarding the definition of cycling policies and infrastructure.

The third section introduces the research case study, the city of Madrid, providing a necessary local context in order to understand the research conducted. The section describes general mobility patterns and the state of cycling culture in Madrid, including the recent emergence of BiciMAD (Madrid Bike Share System), as well as it introduces to current cycling policies and measures and future plans in the city of Madrid.

The fourth section is focussed on the visualisation of the cycling flow derived from the Madrid Bike Share System (BiciMAD) activity, obtained by processing over 250,000 GPS routes, and on providing an analysis of how this flow is distributed across the urban street-network, at different moments. It explores the diverse levels of activity over the course of the day, and during the weekdays, weekends or holidays, as well as the different cycling patterns of frequent and occasional users. The section is based on the research synthesized in the paper titled *"The pulse of the cycling city: visualizing Madrid Bike Share System routes and cycling flow*" (Romanillos, Gómez-Moya, Zaltz-Austwick, & Lamíquiz-Daudén, 2018), a research also developed within the context of this thesis and published in Journal of Maps in Mars 2018.

The fifth section describes the development and results of the *Madrid Cycle Track* initiative (www.huellaciclistademadrid.es), an online platform launched with the aim of collecting cycling routes and other information from volunteer cyclists and messengers. It also illustrates, for the first time, the real flow of casual cyclists and bike messengers in the city of Madrid, through a number of online maps embedded on the digital platform, and through a map that represents cyclists' routes according to the purpose of the journey. This section essentially describes the research titled "*Madrid cycle track: Visualizing the cyclable city*", published in Journal of Maps in 2016, as part of this thesis. The research provides an analysis of casual cyclists' routes according to the purpose of the journey, the average speeds, distances, travel times, accumulated elevation gain, the type of bike used and also compares the results to the ones obtained with bike messengers.

The sixth section pursues different objectives. The first goal is to analyse the impact of a wide range of factors on cyclists' operating speeds. Based on the detailed examination of thousands of GPS routes, we conduct diverse OLS regression models in order to analyse cyclists' speed according to the diverse local factors that affect cyclists along the different street segments of their journey, such as the slope, the existence –and type– of bike infrastructures, the average traffic speed or the distance to traffic lights or intersections. Cycling speed is also analysed according to cyclists' gender or age, as well as according to the purpose of the journey, or even the weather conditions. The research includes the analysis of regular cyclists' trips, as well as the analysis of bike-messengers' routes.

The analyses conducted shed light on the influence of these factors on cyclists' speed by quantifying their specific impact, and diverse models predict cyclists' travel times for the whole street network, in the current scenario but also in future ones that may correspond to the implementation of new infrastructure or policies. In addition, the models allowed us to pursue the second goal of this section: to conduct a comparative analysis of accessibility for different transport modes, and then evaluate the competitiveness between them.

The sixth section corresponds to the research synthesized in the paper titled "*Cyclists do better. Analyzing urban cycling operating speeds and accessibility*", submitted to the *International Journal of Sustainable Transportation* in October 2017, accepted and currently under review.

The seventh section discusses the results obtained, in relation to the research questions raised in the introductory section and also in correspondence with the specific objectives originally defined, pointing out the different steps taken to achieve them. The main conclusions are also introduced here, highlighting the main findings, the potential application of the outputs in order to serve as tools for defining better policies and designing better infrastructure and, of course, underlining also the main limitations. Finally, future research lines are presented here, with a special emphasis in pointing out the possibilities that the new data sources are bringing for the execution of more dynamic analysis of mobility.

Finally, in addition to the main text, the thesis includes some supplementary content. The first one is a video visualization that illustrates casual cyclists and bike messengers' cycling flow over the course of a day in the city of Madrid (Link to visualization on the website), already published in the paper titled "*Madrid cycle track: Visualizing the cyclable city*" (Romanillos & Zaltz Austwick, 2015). The second one is another video visualization (Link to visualization on the website) that similarly illustrates the cycling flow derived from the BiciMAD, over the course of a day, a video which is part of the paper titled *"The pulse of the cycling city: visualizing Madrid Bike Share System routes and cycling flow"*, submitted to Journal of Maps in December 2017. Finally, it is important to make reference to the different online content embedded in the website www.huellaciclistademadrid.es, which was the core of the Madrid Cycle Track initiative, launched with the aim of collecting cyclists' GPS routes, and which now essentially hosts a number of online maps that illustrate the cycle track of the different groups of cyclists that we studied throughout these years, allowing a more dynamic exploration and visualization of the cycling flow.

2 Background

2.1 Introduction

Over the past years, many cities all around the world have been promoting cycling as a sustainable mode of transport that promises to bring a wide range of benefits related to different social and environmental aspects. Changing long-standing travel behaviour patterns is a huge endeavour, and in order to accomplish this transport modal shift, cities have invested important resources in providing cycling infrastructure and implementing different pro-bicycle policies and measures. In this endeavour, cities are often supported by national and international institutions and organizations, which have been promoting the development of a wide range of programmes with the aim of increasing cycling and improving cyclists' safety.

At the same time, cycling has been the focus of attention of an increasing number of studies within the academia and the scientific community. Cycling mobility is been currently analysed from multiple perspectives by researchers from many different disciplines, from phycologists to transport engineers, from social-scientists, urban planners or geographers, to data scientists or computer developers. This relevant multidisciplinary approach reflects the complex nature of cycling mobility, and the fact that the research production on cycling mobility has grown exponentially evidences the extraordinary interests of this field of knowledge.

This section aims at summarizing the most important research approaches and advances on cycling mobility, as well as the most relevant and recent planning and policy practices that are being promoted by different institutions and organizations with the aim of fostering urban cycling mobility. Although the work developed by the academia and the institutions is often related, unfortunately, in many cases it follows separate and parallel paths. In consequence, on the one hand, it is common to find practices that do not consider the latest research advances, and continues to provide solutions based on obsolete methodologies or data. And on the other hand, it is also common to find research explorations that do not take into considerations the real needs and problems of cities in their effort of defining policies and planning infrastructure. This research aims at providing a contribution to the existing research on cycling mobility, increasing the existing knowledge in some specific research lines, as well as at bringing new methodologies and tools for urban planners and decision makers. With these two objectives defined, the present background on cycling mobility provides a double context, with the aim of defining a theoretical framework that allows us to understand the research developed and the contributions in the different fields.

2.2 Current research approaches

The numerous academic studies on cycling mobility can be classified according to a number of research lines. Although this thesis only contributes directly to some of them, the topic addressed, the analyses conducted, the results obtained and the conclusions drawn are related to most of the central questions at the core of all the different research lines defined. We will describe briefly the main questions addressed by each line, and we will include some of the most relevant contributions that are, inevitably, just a sample of the immense work in progress.

Finally, we will highlight the potential interest or the relationship between this thesis and the questions addressed by each research line, when these connections can be established. The main research lines considered are:

2.2.1 The role of infrastructure on cycling mobility

The understanding of urban cyclists' preferences and decisions is crucial to planning and designing infrastructure and services in an efficient way. With regard to cycling infrastructure, the assertion "*Bicycle lanes were never neutral, but contested from the start*", stated in the review on the history of "*Bicycle lanes in Urban Europe, 1900-1995"*, conducted by Oldenziel & Albert de la Bruhèze (2011), reflects quite well the existing controversy around the provision of cycling infrastructure, against the popularly believed consensus about its necessary development. Although many citizens demand the implementation of separate bike lanes, some cycling associations hold a contrary opinion, and oppose their implementation (Bravo, 2016) in cities like Madrid, basically arguing that the best strategy to foster cycling is to promote the coexistence of cycles and motorised traffic on roads through other measures such as traffic restrictions, traffic speed reduction and pro-bicycle policies aimed at arriving to a minimum cycling flow that may guarantee the safety of cyclists as a significant and respected part of the daily traffic on every road.

However, research on the role of cycling infrastructure clearly evidences the common preference of cyclists for using different types of bike facilities. As the study conducted by Nelson & Allen (1997) clearly states in its title, summarizing the results and an extensive analysis of 18 large cities across the United States: *"If you build them, commuters will use them: association between bicycle facilities and bicycle commuting"*. The study was based on a cross-sectional analysis, controlling for a variety of extraneous factors, which allowed the authors to evaluate and attribute the differences in bicycle commuting to the overall supply of pathways. This analysis was extended to 43 U.S. cities in a new version of the study, with comparable result, entitled in a similar way by Dill & Carr (2003): *"Bicycle commuting and facilities in major US cities: if you build them, commuters will use them"*.

Years later, the study conducted by Tilahun, Levinson, & Krizek (2007) went one step further and evaluated the preference of cyclists for several types of bike lanes through an adaptive stated preference survey, that revealed the extra time that cyclists are willing to travel when using the different kinds of facilities (off-road bicycle facility, bike-lane without parking, bike-lane with on-street parking, etc.) rather than an unmarked on-road facility with side parking. The adaptive nature of the survey allowed the researchers to know the exact additional minutes each individual was willing to travel on an alternate facility.

More recently, Broach, Dill, & Gliebe (2012) evaluated cyclists' preferences for different facility types by analysing almost 1,500 GPS tracks provided by 164 cyclists in Portland, Oregon. The results also evidenced the preference for off-street bike paths and bike lanes, as well as bridge facilities and bikeways with traffic calming features. A detailed review of similar studies, based on new location-based data, will be provided in the next section.

In addition to the studies focused on evaluating the impact of different cycling facilities, other studies have been centred on building bicycle facility planning models. As Rybarczyk & Wu (2010) summarized, these models can be divided into two groups: supply-based models and demand-based models. Supply-based models essentially propose the implementation of infrastructure along the main arteries or collectors according to the roadway conditions and the level of comfort associated to them, assessed through quantitative models, such as the Bicycle Level of Service (BLOS), developed by Landis, Vattikuti, & Brannick (1997) or the Bicycle Compatibility Index (BCI) proposed by Harkey, Reinfurt, & Knuiman (1998). Demand-based models propose the provision of cycling infrastructure by predicting bicycle travel demand, based on different methods: aggregated behaviour studies, discrete choice models and others, such as the Latent Demand Score (LDS) proposed by Landis (1996).

This thesis may contribute to the discussion on the preferences of cyclists regarding the different types of bike facilities and to the effects they have on the variation of cycling flow, since the impact of different facilities on cycling operating speeds and travel times, and the preference for its use according to the purpose of the journey, gender or age, is evaluated. Actually, the GPS routes were map-matched to a detailed street network based on the *TomTom®* Spanish road network, the most accurate street network found in Madrid, contemplating not only roads but also pedestrian streets and bike infrastructure, and includes over 160,000 street-segments for the metropolitan area of Madrid that cover the collected cycling routes. Although the *TomTom®* street network was supposed to contemplate the existing bike infrastructure, it was not complete. Because of this, the network was edited and the bike infrastructure updated, including all the eight different kinds of bike infrastructure considered in the Madrid Cycling Master Plan: Bike lane on the sidewalk, segregated bike lane on the sidewalk, non-segregated bike lane, segregated bike lane in parks/countryside with adapted surface, segregated bike lane in parks/countryside without adapted surface, segregated bike lane in parks or in the countryside with a slightly adapted surface, lane shared with cars (no infrastructure) and "lane with cycling preference and speed reduction".

2.2.2 Analysis of cycling route choice

Whether to choose the shortest route or an alternative longer path equipped with any kind of cycling facilities, is just one of the decisions cyclists use to make. In order to perform a more comprehensive analysis of all the potential factors affecting the decision of taking one path or another, the analysis of the impact of cycling infrastructure was extended, from the very beginning, to the general analysis of cyclists' route choice, and different studies focused on developing route choice models based on the application of diverse techniques to different kind of data.

With different objectives, cyclists' preferences and decisions have been traditionally analysed through the information derived from household surveys or more specific group surveys. Regarding the areas of demand analysis, preference evaluation and forecasting, Stated Preference (SP) techniques have been commonly applied (for example, Kroes & Sheldon (1988)), in order to measure the effects of certain improvement on cycle facilities and then forecast the effect of others (Hopkinson & Wardman, 1996) or with the aim of estimating the potential cycle demand in certain urban areas (Ortúzar, Iacobelli, & Valeze, 2000). Also Revealed Preference (RP) studies have been conducted with different purposes, such as the development of mode choice models (Noland & Kunreuther, 1995).

More specifically, concerning the spatial analysis of cycling for planning purposes, Stated and Revealed Preference methods have been the dominant techniques. In SP studies, respondents were typically asked to evaluate the impact of different factors on their cycle route choice, or to state their preference for a street or a route by evaluating the options using photos of the routes or locations (Bradley & Bovy, 1984; J. Larsen & El-Geneidy, 2011; Tilahun et al., 2007). Some RP based studies asked respondents to design their cycle route on a map (Ben-aiuva & Morikawa, 1990) and finally, some approaches involved both SP and RP techniques but still using similar methods (Yang & Mesbah, 2013).

In recent years, the research on the spatial dimension of cycling mobility has grown substantially, and shifted with the emergence of new location-based data allowing more complex spatial analysis. Recent investigations have studied two different types of location data: point data captured by the growing Bike Share Systems spread around the world (Etienne & Latifa, 2012; Froehlich et al., 2009; O'Brien et al., 2013; Zaltz Austwick et al., 2013b) and GPS tracking data collected through smartphones applications or specific devices, gathered specifically with research purposes or made available by "Big App" Companies for research or planning (Broach et al., 2011; Harvey & Krizek, 2007; Menghini et al., 2010).

By overcoming the traditional SP and RP limitations in terms of high costs, small samples and spatial imprecision (Hood, Sall, & Charlton, 2011), these new studies are improving the understanding of urban cyclist behaviour and producing outputs to inform the planning and design of bike infrastructures and policies. An extensive review on these new studies based on new location-based data will be provided in the next section.

This thesis provides a relevant collection of GPS cyclists routes which can be the base for developing a route choice model focused on the analysis of the impact of a wide range of factors on casual cyclists, bike messengers and Public Bike Sharing users. This analysis is actually among the most relevant future research lines, based on the data already collected, that will continue the work started here. The information collected along with the GPS routes, regarding different characteristics of the cyclists (such as age or gender), variables related to the journey (such as the purpose of the journey, travel distance, travel time, accumulated elevation gain or loss) or other variables related to the street network (such as the slope, the type of bike infrastructure implemented, the existence of traffic lights, etc.) or other urban conditions (motor traffic speed or density, for instance), brings the possibility of performing a route choice model in detail, covering all these variables as potential factors that influence the decision of choosing one path or another.

2.2.3 Analysis of cycling behaviour

Although, as we have seen, there is a demonstrated correlation between certain aspects of the built environment (such as the existence and type of bike infrastructure) and the decision to cycle for transportation (Broach et al., 2012; Nelson & Allen, 1997), improvements to the built environment or the implementation of cycling infrastructure are not sufficient to encourage cycling. There are a wide range of factors of different nature that influence cyclist behaviour or people willingness to cycling.

Willis, Manaugh, & El-Geneidy (2015) recently conducted an extensive review of 24 previous studies, published between 2005 and 2012, focussed on analysing the influence of social and psychological factors on the choice to cycle for transportation. The research highlight the relevance of perceptions, attitudes, habits and social environments on cycling. Among the most relevant results, we can highlight the difference between the real and the perceived barriers to cycling, with non-cyclists more likely to mention barriers to cycling and evaluate them in a more negative way.

Similarly, the study conducted by Ma, Dill, & Mohr (2014) titled “The objective versus the perceived environment: what matters for bicycling?”, evidenced the importance of promoting along with improvements of the environment, interventions just focussed on changing the perceptions of the build environment, such as information about bicycle safety facts, educational activities, marketing materials and public events such as closing streets to cars for several hours during weekends or holidays, etc.

With a similar focus, the research titled “Analysis of perceptions of utilitarian cycling by level of user experience”, conducted by Rondinella, Fernandez-Heredia, & Monzón (2012), provides a more detailed study, integrated in a broader research on the role of mode familiarity, crystallised in the thesis titled “Considering cycling for commuting the role of mode familiarity: an exploration on the (circular) relation between cycling behaviours and attitudes toward cycling in Vitoria-Gasteiz, Spain” (Rondinella, 2015). This research, based on a telephone survey in a representative sample of 746 commuters in the Spanish city of Vitoria-Gasteiz, explores what Rondinella calls “the cycle of cycling consideration”, highlighting the fact that individuals need to have positive beliefs about cycling in order to consider it, something unlikely to happen with the low levels of familiarity characteristics of low-cycling contexts. Base on the same data, a complementary analysis is provided by (Muñoz, Monzon, & López, 2016), exploring other key factors influencing bicycle commuting and proposing a methodology for including cycling-related indicators in mobility surveys based on the Theory of Planned Behaviour (TPB).

Beyond the analysis of cyclists’ perceptions and beliefs, other studies have focused on the analysis of cyclists’ attitudes. For instance, in the study titled “Four types of cyclists? Examination of typology for better understanding of bicycling behaviour and potential”, conducted in Portland, Dill & McNeil (2013) classified cyclists into four different categories (Strong and the Fearless, Enthused and Confident, Interested but Concerned, and No 5 Way No How) based on their stated level of comfort cycling on different facility types, their interest of cycling beyond the transportation purpose, and their physical ability to bicycle. A majority of the 908 respondents fit in the Interested but Concerned category, and allowed the researchers to collect information on different interventions that could potentially change the attitude of cyclists and potential cyclists, such as increasing separation between bicycles and motor vehicles, reducing traffic speeds or building certain facilities.

Finally, other studies focus on explaining gender difference in bicycling behaviour (Emond, Tang, & Handy, 2009). Although men and women bicycle at relatively equal rates in countries such as the Netherlands, Germany, and Denmark, research has consistently found that in the United States men's total bicycle trips surpass women's by a ratio of at least 2 to 1, and this ratio is even lower in the case of other countries such as Spain. In the case of Madrid, around the 80% of daily cyclists are males (Monzon de Cáceres, Rondinella, & Muñoz López, 2011). Although the reasons behind these dramatic differences willingness to cycling according to gender may be of different nature in each country or city in particular, some studies have found common patterns in aspects such as the impact of different cycling facilities according to gender (Krizek, Johnson, & Tilahun, 2005).

This thesis contributes to the exploration of cycling behaviour, analysing questions such as the different cycling patters according to the purpose of the journey, the influence of weather conditions or cycling mobility according to gender, providing information about male-female rates, and identifying different patterns on aspects such as cycling speeds, travel distances, travel times or the impact of certain cycling infrastructure.

2.2.4 Estimation of cycling demand and cycling flow

Traditional approaches to modelling cycling demand are based on descriptors of population, land-use, bicycling facilities and environmental characteristics (Barnes & Krizek, 2005), in close relation to the more general analysis founded on the "3D" principle of the influence of density, diversity, and design on travel demand (Cervero & Kockelman, 1997).

In the particular case of cycling demand, different studies have focused on the effects on more specific variables that particularly influence cycling behaviour. For instance, Cervero & Duncan (2003) analysed the role of the built environment and what the call urban landscapes on cycling demand, focusing on urban design and land-use with special attention on factors that represent potential barriers to walking or bicycling. Regarding the role of environmental factors, it is interesting the distinction made by Dill & Voros (2007) between the environmental factors that can be measured objectively (e.g., number of miles of bike lanes, average temperature, and street connectivity) and subjectively (e.g., people's ratings or perceptions of the bicycling environment), evaluating separately the role of both on the levels of cycling, and including other variables such as the attitude of cyclists along with more traditional factors such as demographics.

Other studies have been concentrated on developing methodologies aimed at estimating the potential cyclist demand for future scenarios, based on the analysis of the current activity —through counts at different locations (J. Hudson, Qu, & Turner, 2010; Turner, 1998) —, or based on household surveys that includes stated preferences experiments for potential cycle users, such as the study conducted by Ortúzar et al. (2000), which included a wide range of factors, including the existence of cycling infrastructure, weather, safety and even the cultural factor, related to the level of familiarity of citizens in general to the cycling mobility.

More recently, another research line started to study cycling demand based on the spatial analysis of urban network, essentially by examining the accessibility of streets according to *centrality* measures, such as *betweeness*, and considering *angular distance* rather than *metric distance*. In rough terms, "*betweenness* is the output of a flow model which simulates indiscriminate trips from everywhere to everywhere, subject to a maximum trip distance or radius, and some criteria by which each trip is routed" (Cooper, 2017), and other authors have shown the relevance of this street network based accessibilities for pedestrian or automobile mobilities, using Madrid as a case study as well (Lamíquiz & López-Domínguez, 2015).

The research conducted by Raford, Chiaradia, & Gil (2007) in London, applied the *Space Syntax* theory (Hillier, 1997; Hillier & Hanson, 1989) and after applying an *Angular Segment Analysis* (ASA), found that cyclists minimized *angular distance*, pointing out that estimating least angle routes in urban environments is a useful way of predicting cyclist flow and route choice. Actually, in this study, angular distance turned out to be the dominant explanatory variable, correlating to nearly 70% of the observed cyclist volume. This surprising result could be influenced by the number and location of counts in which it was based, since further studies based on the application of similar methodologies obtained more modest —though yet significant— correlations (Criollo Preciado, 2012).

Other studies focused on estimating cycling flow combined the spatial analysis of urban networks with other variables and obtained greater correlations. For instance, the research conducted by McCahil & Garrick (2008) included, in addition to Space Syntax measure *choice*, other variables such as population density, worker density, obtaining a R-Square value of 0.8016 (considering logarithmic transformations). Another example is the recent study conducted by Cooper (2017), obtaining good results when considering angular measures and including in the analysis an hybrid betweenness measure along with other variables such as vehicle traffic or slope.

This thesis is close related to the research line focused on the estimation of cycling demand and cycling flow, since one of its goals is to estimate the distribution of cycling flow by processing the collected routes. The thesis may contribute to feature research that could take advantage of the large data sample, avoiding possible over—or under— estimations when performing the different regressions aimed at predicting cycle volume from a number of explanatory variables. Actually, the regression models may find a strong foundation in the ones developed in the context of this thesis when predicting cyclists' operating speeds and travel times, since most or the explanatory variables considered here may applicable to the new regression models to develop.

2.2.5 Public Bike-Sharing Systems

Although Public Bike-Sharing programmes have existed for over 50 years, they have grown exponentially over the past 10 years, gaining popularity worldwide (Fishman et al., 2013), and also more particularly in Spain (Anaya & Castro, 2011). In consequence, recently literature on Bike Share Systems (BSS) has been growing equally, focusing on the analysis different aspects of this emergent phenomena.

The extensive review conducted by Fishman et al. (2013) provided a rich and critical overview of the growing body of research on these programs. Different studies have analysed the use of BSS from different perspectives. Some reports have analysed the demographics of Bike Share users, uncovering significant differences from the general population demographics, finding, for instance, significantly higher employment rates and education levels, lower average age, and more likely to be male (LDA Consulting, 2012).

Other studies have been centred on the analysis of BSS activity, visualising their dynamics and identifying trends usually based on the analysis of the docking stations' performance, related to the number of trips starting and ending at the station level (Borgnat et al., 2013; Zaltz Austwick, O'Brien, Strano, & Viana, 2013a). Other studies have focused on analysing the significant differences in Bike

Share Systems' usage rates that have been found globally, from three to eight trips per bicycle per day (Fishman, 2011; Meddin, 2011; Rojas-Rueda, de Nazelle, Tainio, & Nieuwenhuijsen, 2011).

An important number of studies have analysed the BSS imbalances produced by the different levels of attraction and generation of trips at the station level (Goodman & Cheshire, 2014), often with the aim of developing efficient bike redistribution strategies (J. H. Lin & Chou, 2012; Raviv, Tzur, & Forma, 2013). Similarly, with the aim of implementing more balanced BSS, other researcher have modelled demand (Systems & Lackner, 2013) or have developed models that optimize the location of BSS stations (García-Palomares, Gutiérrez, & Latorre, 2012).

This thesis contributes to the existing research on Public Bike-Sharing Systems, by including a specific section focused on visualizing the cycling flow derived from the Madrid Bike Share System (BiciMAD) activity, and on providing an analysis of how this flow is distributed across the urban street-network, exploring the diverse levels of activity at different moments (over the course of the day, and during the weekdays, weekends or holidays) as well as the different cycling patterns of frequent and occasional users. In addition, this thesis also includes an analysis of the accessibility provided by BiciMAD, comparing the different areas covered by this and other public transport modes, according to different travel times. Finally, this thesis provides the bases for future research, such as a more detailed and dynamic analysis of accessibility, which will analyse the different accessibility scenarios that correspond to different moments.

2.2.6 Bicycling as a sustainable transport mode: the environmental and social benefits of cycling

Promoting a more sustainable transport, defined as ''satisfying current transport and mobility needs without compromising the ability of future generations to meet these needs'' (Black, Paez, & Suthanaya, 2002), has become one of the most important goals in transportation planning and research, and some authors (Newman & Kenworthy, 1999) have stated that an ideal *sustainable postmodern city* should include a prominence of walking, cycling, public transit, cars as supplementary, and air just for global transit (Rybarczyk & Wu, 2010).

In this context, cycling is being promoted in many cities all around the world, since it is considered the most sustainable urban transport mode after walking:

> *"Cycling is indisputably a green activity (…). The bicycle is one of the most environmentally-friendly machines ever invented. Cycling pollutes neither land nor the atmosphere, is kind to wildlife, and reduces the amount of land that needs to be covered with concrete and asphalt"*. *How to be Green* (Button, 1989).

> *"Cycling causes virtually no environmental damage, promotes health through physical activity, takes up little space and is economical, both in direct user costs and public infrastructure costs. In short, cycling is environmentally, socially and economically sustainable"*. *Cycling towards a more sustainable transport future* (Pucher & Buehler, 2017).

"Cycling is probably the most sustainable urban transport mode, feasible not only for short trips but also for medium-distance trips too long to cover by walking". Making Cycling Irresistible: Lessons from the Netherlands, Denmark and Germany (Pucher & Buehler, 2008).

The research focused on analysing the sustainable dimension of cycling and on highlighting its environmental and social benefits is extensive, and covers a wide range of aspects. A first group of studies focuses on studying the environmental benefits of cycling, under the premise that, while private motor vehicles —essentially cars— contribute to air pollution, traffic congestion, active modes of transport (walking and cycling) provides substantial benefits for health, social equity, and climate change mitigation (Macmillan et al., 2014).

A second group of investigations is centred on analysing the benefits that cycling brings to public health. As summarized by Pucher, Dill, & Handy (2010), *"Bicycling is healthy. That is the conclusion of an increasing number of scientific studies assessing the impacts of bicycling on levels of physical activity, obesity rates, cardiovascular health, and morbidity"*.

Thus, an important number of investigations analysed the impacts that a shift from car to cycling or walking could bring to public health, such as the study conducted by Rabl & de Nazelle (2012), who evaluated specifically four effects: the change in exposure to ambient air pollution for the individuals who change their transportation mode, their health benefit, the health benefit for the general population due to reduced pollution and the risk of accidents.

A number of studies have focused on more specific relationships between cycling mobility and public health. For instance, the study conducted by Rojas-Rueda et al (2011) examined the risks and benefits to health provided by bicycle sharing schemes, compared to the use of car in urban environment, assessing quantitatively the reduction in mortality associated to the decrease of carbon dioxide emissions, using as a case study the city of Barcelona. Other investigations studied the promotion of cycling as potential "solution" to physical inactivity, which is proved to be associated to important diseases in many countries (Bauman, Titze, Rissel, & Oja, 2011).

This thesis is not directly related to this research line on cycling mobility, environment and health, but provides information that may be of interest for other studies aimed at monitoring the evolution of cycling activity in the city of Madrid, relating it with the trends on the use of private car. In addition, it might provide the basis for evaluating the exposer of cyclists to air pollution, since this research reveals what are the most important arteries in terms of cyclist flow and in consequence, it is possible to study how exposed cyclists are according to the air pollution levels detected in these particular corridors.

2.2.7 Bicycling and safety

Another significant research line on cycling mobility have focused on studying its safety and analysing the risks that it involves, and the impact of different policies and infrastructure on the evolution of accidents and crashes. But, first of all, is it cycling a dangerous activity? Contradicting this widespread misperception, the research conducted by Pucher, Dill, & Handy (2010) reviewed diverse studies that indicate that the health benefits of bicycling far exceed the health risks from traffic injuries. Moreover, different studies (Elvik, 2009; Robinson, 2005) have proved that, as bicycling levels increase, injury rates fall, making bicycling safer and providing even larger net health benefits. For instance, in the study *"Safety in numbers: more walkers and bicyclists, safe walking and biking"*, Jacobsen (2003), examined the relationship between the numbers of people walking or bicycling and the frequency of collisions between motorists and walkers or bicyclists, founding a non-linear relationship, such that collisions rates declined with increases in the numbers of people walking or bicycling in a significant way.

Although the reduction of accidents, once certain level of cycling activity is reached, is obviously a positive finding, the truth is that, in order to reach those levels of activity, some measures must be taken in order to guarantee a minimum safety. Building infrastructure and facilities is one of the most common measures and the body of research around the impact of different types of transportation infrastructure on bicycling injuries an crashes is quite extensive, as the review of the literature conducted by Reynolds, Harris, Teschke, Cripton, & Winters (2009) evidences.

This thesis explores different aspects that may contribute to further analysis on bicycling and safety. For instance, the study of cyclists' operating speeds provides information about one of the variables that must be introduce as input in most of the analysis carried out when exploring accidents, crashes and the level of confront and confidence shown by the different types of cyclists. We also explore the variations of speed at intersections or traffic lights, finding evidences about whether these traffic lights are respected or not according to the different types of cyclists or at different moments of the day. Finally, the collected cyclists' routes are informed with data regarding real traffic volume or speed, or about the existence or not of different kinds of cycling facilities, all of them variables that can be useful in future research built upon this thesis.

2.2.8 Integration with other transport modes

The integration of cycling with other transport modes is one of the goals that many cities, especially major ones, are pursuing, with the aim of promoting transport multimodality and obtain the benefits that an integrated transport network provides in cities (Givoni & Banister, 2010).

Transport systems are getting more and more complex in cities, and different transport alternatives are continuously emerging (bike sharing schemes, car sharing systems, companies like Uber or Cabify, etc.), creating a transport ecosystem difficult to manage in an integrated way. As Givoni & Banister (2010) clearly explain, "As the transport system has grown and developed over time, and as new modes of transport have been introduced, specialization has taken place in which those involved with the supply, operation and management of the transport system have tended to focus on one or a limited sub-set of the transport system components."

In this context, a research line emerged with the aim of analysing the levels of integration of cycling and disseminating the most successful policies and experiences. Studies, such as the one conducted by Olafsson, Nielsen, & Carstensen (2016), analysed the multimodal behaviour in Denmark according to different travel purposes, identifying distinct modality styles. An extended analysis to the European scale was conducted by Martens (2004), including countries with a widely differing bicycle cultures and infrastructure, and exploring the levels of bicycle ridership according to travel distances, travel purposes and the impact of car availability.

Some other studies analyse the emergent policies launched with the aim of promoting cycling for the first-and last-mile of public transit connections, with special attention to the cycling accessibility to train stations (Rietveld, 2000) or in the case of the particular integration of public bike-sharing systems (Parkes, Marsden, Shaheen, & Cohen, 2013).

Although the analysis of cycling in transport multimodality is out of the scope of this thesis, it can contribute to further studies of the existing integration of cycling and other public transport modes, since it explores the cycling flow and activity close to transit hubs or relevant public transport stations.

2.2.9 Bike messengers

As Ducret & Delaître (2013) explain, the CEP sector (courier, express and parcel service), particularly the final stage of the supply chain in cities, has undergone significant changes for the last ten years, essentially due to the spread of new technologies that led to new shopping patterns, such as distance selling and electronic commerce, questioning the retail sector. Changes that have led to growth in parcels volume and in home deliveries in particular.

In this context, and with the aim of promoting a more sustainable logistic chain, many cities are stimulating the emergence of new bike messenger companies. As Maes & Vanelslander (2012) clearly described, “As vans are polluting urban areas and furthermore losing an enormous amount of time and money in congested areas, the issue of the last mile is gaining importance. As such, a shared incentive for privately operating companies and governments (at a national and certainly at local level) can be seen to stimulate alternative transport concepts, ideas of city depots, the use of inland waterways to deliver in city centres, electrically-powered vehicles, shifting to night transport etc. are getting increasing attention. Local governments want to decrease the number of vans and trucks running around in city centres.”

Although the existing research focussed on analysing bike messengers is not extensive yet, it is included in this review because its recent emergence and the interest that it has for some questions addressed in this thesis. Some studies, such as the one conducted by Fincham (2007) analysed the history and basic sociodemographic characteristics of bike messengers, analysing also questions such as their identity and sense of community. The study revealed interesting information of the bike messenger community in the United Kingdom. For instance, some facts analysed in the book: the large majority of bike messengers are men, with just about one in six women. Their average age usually ranges from 25 to 31 years old, and they tend to work as messengers for approximately three to four years.

Different studies have analysed the implications of considering bike messengers for freight transport at a physical level, something that is not trivial, considering that working as a bicycle messenger demands a very high physical capacity. In this sense, the study conducted by Bernmark, Wiktorin, Svartengren, Lewné, & Aberg (2006) focused on determining the level of energy expenditure and exposure to air pollution for bicycle messengers. As they describe in their study, “A working day normally includes 70–100 km of cycling and 20–60 stairs of walking carrying weights of 2–20 kg on the shoulder. Some of them work only part-time but the majority are full-time employees (40 h per week)."

Other researchers analyse whether this emergent phenomenon can be a real alternative to motor based freight transport, given the fact that bike couriers essentially delivers post, parcels or freight with a low volume of weight. In this sense, the research developed by Maes & Vanelslander (2012) talcked the question of whether these companies can be an economic viable alternative for fossil fuel powered transport, and if so, in what markets these opportunities can be found.

This thesis contributes in a way to this emergent research line focused on the analysis of bike messengers' activity and behaviour, since it includes the analysis of bike messengers' routes –as far as we know, for the first time–, operating speeds and cycling flow, based on the collection of GPS routes and associated information from four different companies operating in Madrid.

2.2.10 Research on current planning and policy practices

Over the past years, a growing body of research has been centred on the analysis of current programs, planning and policy practices oriented to foster cycling mobility. The content of these different programmes and practices will be reviewed in the next section, and what is provided here is a synthetic classification and description of the different studies conducted.

An important number of studies have focussed on general analysing on the effects of a wide range of interventions in the levels of bicycling. One of the most remarkable example of this investigations is the one conducted by Pucher, Dill, & Handy (2010), who reviewed 139 studies, based on a broad variety of methodologies.

In addition, it's significant the number of studies that provided comparative analysis of the different policies launched in different countries and the different cycling trends found in them, as a consequence. A remarkable contribution is the one led by John Pucher through different studies. For instance, the comparative analysis of bicycling trends and policies in Canada and The United States, trying to find out the reasons why Canadians cycle about three times more than Americans (Pucher & Buehler, 2006), the comparative analysis between the Netherlands, Denmark and Germany (Pucher & Buehler, 2008) or the comparative analysis between Sydney and Melbourne cycling activity and policies (Pucher, Garrard, & Greaves, 2011) or

Finally, other studies have analysed the effects of particular policies or measures, or focussed on the analysis of different interventions at one particular place, such as Pucher (1997) in his study *"Bicycling Boom In Germany: A Revival Engineered by Public Policy"*, or the particular analysis of the changes on cycling mobility that smart bikes sharing programs are providing in the United States (DeMaio & Gifford, 2004). Some scholars have concentrated their research on identifying the policies and measures that successfully promote a modal shift from car to cycling mobility. For instance, in their study *"Promoting walking and cycling as an alternative to using cars: systematic review"*, Ogilvie, Egan, Hamilton, & Petticrew (2004) assessed what interventions are effective in promoting a population shift from using cars towards walking and cycling and the health effects of such interventions. Finally, in this sense, particularly interesting is the critical analysis on the real effects of certain policies on mode substitution and the derived impacts is provided by Fishman et al. (2013). According to them, we cannot assume that a significant proportion of users are transferring to public bicycle from single occupant car use. "Yet, a wide range of papers from a number of countries have reported that this is seldom the case".

Although this thesis does not contribute to this body on research centred on analysing current planning and policy practices, it provides the basis for future investigations oriented to study the impact of different planning initiatives and policy measures that have been or are being promoted in the case study, the city of Madrid. The different levels of cycling flow or activity in general, visualised and analysed here, can be studied with regard to the areas where different measures have been implemented, and thus, it will be possible to assess their effectiveness.

As previously mentioned, while this section provides brief overview of the different studies focussed on analysing current planning and policy practices, the next section is focussed on providing a review on the content of these different programmes and practices.

2.3 New data sources, new research approaches: Big data and cycling.

Remarks

This section provides an extensive review of the data sources and the associated new research opportunities, based on the review paper entitled *"Big Data and Cycling"* (Romanillos et al., 2016), a research developed within the context of this thesis and published in *Transport Reviews* in 2016.

Access to paper: https://www.tandfonline.com/doi/abs/10.1080/01441647.2015.1084067

2.3.1 Introduction

Big Data holds the promise to illuminate social processes that were previously undersampled or poorly understood. For those involved in city planning, service provision, and business intelligence, it still remains central to innovation and research. The term arose first from the large-scale collective efforts of scientists at the CERN (*Conseil Européen pour la Recherche Nucléaire*) particle accelerator, large scale astronomy and genomics projects (Marx, 2013) – but for more than five years, the potential for working with large-scale social data has been grasped by the commercial sector (Manyika, 2011) as well as governments and non-governmental organisations (NGOs) (Hall, 2012). Despite the excitement it has generated, working definitions of the term are problematic – the most widely adopted framework derived from Laney (2001) refers to the "3Vs" of Big Data: Volume (size), Velocity (speed of generation or collection) and Variety (synthesizing a range of sources). Later authors (Kitchin, 2014) have added additional definitions to this (including "Veracity", the quality of the data – as a way to preserve the alliteration of the concept), but it seems dubious that, in the wider world of Big Data, many data sources fully qualify under all the categories of the 3Vs, or the wider definitions.

Most of the data sources discussed in this review qualify as Big Data under the first V (Volume), but possibly not the others – many are single source (e.g. a transport provider or single app or web platform, disqualifying them under the *variety* criterion) and few provide large velocities of data in real-time.

It perhaps makes sense to view the concept of Big Data as representing an enthusiasm for the rapid expansion of data availability. Within these technologically-driven definitions, there is no focus on openness or accessibility. While the promise of innovation and new markets may motivate engineers and computer scientists, it is the availability of data that has empowered and excited new actors in policy, politics and governance. New datasets have become widely accessible which capture the detail of processes that previously were estimated, under sampled, kept private, or simply poorly understood. In part, the Open Data movement can be thanked for its hand in not only pushing an agenda of transparency, but encouraging service providers and government departments to provide usable datasets and streaming APIs (Application Programme Interfaces) that third parties can use to create commercializable platforms and research outputs. The topics of data released as a result of a movement towards Open Government Data (OGD) arguably has antecedents in census and administrative data, and the transparency agenda has driven the release of largely pre-existing datasets (see, for example, Coleman (2013)). However, the presence of technology as a mechanism of automation and monitoring has generated new datasets with collection methods which are distinct from centrally-compiled or volunteered OGD. This is particularly true in transport, where the automated systems for ticketing or charging create a uniquely detailed data stream – however, this data stream has significant enough privacy issues that it's not yet available in this detailed form. Transport and geolocated data has quite an incredible capacity to de-pseudononymise and reveal new information about individuals (for example, the work done on open data around New York taxis to 'stalk' celebrities or identify the homes of people who go to strip clubs (Tockar, 2014)), so there is a very clear rationale for caution about open data release in this sphere.

Perhaps the most notable example of this data boom is the expansion of smart card systems for public transport in major cities (Pelletier, Trépanier & Morency, 2011) providing journey level information for individual users, in systems that were previously sampled by gate counts and travel-to-work questionnaires. The quantum leap from limited to almost complete sampling is unprecedented, and time slices of this data are available to researchers or developers through service providers online (for example, Transport for London (2014)). Cycling sits in a nexus where availability of Big Data (from quantified self-data, BSP, GPS devices and mobile tracking) intersects with societal needs around fitness, sustainability and air quality, and service provision and infrastructure planning for active transport.

This review seeks to survey the Big Data sources available to cycling researchers, broadly split into *GPS data, live point data,* and *journey data.* These data follow different patterns of volume and velocity, suggesting different problem domains and generating differing analysis approaches. GPS data is collected via smartphone, embedded devices, or specialized units – this is usually collected by individual users within the context of a quantified lifestyle (using fitness, health, and leisure apps), or contributing to a specific study. While this could be shared and acted upon in real time, in many cases users will upload their route at the end of a journey or at the end of the day, putting it in the category of historical data. These provide a high level of data density. Typical GPS data is sampled every few (three to five) seconds, generating hundreds of data points per individual journey, and depending on the sample period, thousands per user, and hundreds of thousands or millions in a typical GPS study (for example, Hood, Sall & Charlton, (2011)). In the case of fitness apps and social media-driven systems, this can number tens of millions of users and routes (Endomondo, 2013; Map My Ride, 2014). Working with GPS data poses some challenges with respect to accuracy (Schuessler & Axhausen, 2009a) and volume, but it has also been one of the more fruitful in terms of the application of models which can link directly to transport planning policy on a city or county level.

Point data refers to information collected at a particular location – an example of this is the information provided by a docking station in a BSP (Froehlich, Neumann & Oliver, 2009), or the data transmitted by a traffic camera or gate counter at a specific intersection (Rogers & Papanikolopulos, 2000). This tends to be smaller in volume, but the increasing availability of this data is starting to allow some extensive insights. For example, the research conducted by O'Brien, Cheshire, & Batty (2013) analysed 38 BSP located in Europe, Asia, the Middle East, Australia and the Americas. Furthermore, through web APIs, BSP can provide information in real time for immediate analysis and response. The rich spatiotemporal characteristics of this data have led to some novel applications of cluster analyses.

Journey data acts at a coarser level than GPS data – providing origin and destination locations and times for individual journey, but not necessarily including detailed information about route choice, detailed link speed and delays. A number of bikeshare programmes (BSP) have released journey data covering a period of months, often amounting to several million journeys, but at present, with some exceptions such as the Capital Bike Share initiative (2015), this data is released months after the fact, making it more amenable to long-term trend analysis than nowcasting or rapid response. The origin-destination datasets allow for space-time and network approaches, and researchers have used route inference to generate the spatial richness of GPS tracks on multi-million journey scale (Zaltz Austwick, O'Brien, Strano, & Viana, 2013), although few estimates of the robustness of these inferences have been carried out.

2.3.2 Research focused on GPS data

Global Positioning System (GPS) technology was originally developed in the 1970s, but despite being available for civil purposes in the mid-1980s, it was only in the 1990s that it became widespread in its integration into consumer devices (Kumar & Moore, 2002). Since then, GPS data have been collected for transport analysis (Shen & Stopher, 2014). Initially, the technology was primarily applied to improve aerial and maritime navigation systems, but since the late-1990s the largest application of GPS has been land transport. Over the last twenty years GPS data has been collected for evaluating system performance such as measuring historical congestion and flow levels, analysing travel behaviour and estimating route choice models (Rasmussen, Ingvardson, Halldórsdóttir, & Nielsen, 2013). In the field of mobility, GPS data have also been collected in the context of household travel surveys, in order to complement the survey responses with detailed trip reporting for a subset of journeys (Bricka, Sen, Paleti, & Bhat, 2012; Doherty, Noel, Gosselin, Sirois, & Ueno, 2001; Ohmori, 2005; Shen & Stopher, 2014).

Since 2007 there has been a substantial rise in the volume of GPS data, due in part to the smartphone "revolution". In 2009 smartphones accounted for 15.4% of the general pool of mobile phones (Li et al., 2010), by 2014 it surpassed 35%, with over 175 billion units (eMarketer, 2014). In the US, it rose from 44% in 2011 to 65% in 2013 (The U.S. Digital Consumer Report, 2014). The generalised presence of GPS technology in smartphones and the vast growth of mobile applications based on location and tracking functionalities also fed this growth. The emergent navigation and the sport/fitness app markets (Evans, 2013; Flurry Analytics, 2014) became apparent more recently, linking personal recorded data to online platforms where people can display and manage their routes and information, and share and compete with other people, creating different user-communities.

In this section, we focus on bicycle riding GPS data collected through mobile applications, GPS devices and online platforms specifically created for each study, and data from big app companies, only recently available for research and planning purposes.

2.3.2.1 GPS data collected through specific research initiatives

The first work analysing cycle mobility through GPS tracks dates from 2007 (Harvey & Krizek, 2007). In spring 2006, the research team launched an initiative to recruit volunteers from different neighbourhoods in South Minneapolis, and finally collected 938 trips from 51 participants (selected according to their age, gender, home location and work location) using GPS devices in order to study commuter cyclist behaviour, analysing chosen routes and their variations due to existing bike facilities. The project remarked on the difficulty of cleaning GPS data, which can contain significant positional inaccuracies - consequently, analysis of cycling behaviour is improved by mapping the recorded GPS tracks onto street infrastructure. Different authors (Wagner, 1997; Marchal et al., 2005 and Schuessler & Axhausen, 2009a) determined diverse approaches to the map-matching process that, with increasing complexity and sophistication, solved the main problems.

The work of Harvey and Krizek provided a descriptive approach to cyclist behaviour. Subsequent studies focused on developing cyclist route choice models from larger samples of GPS routes – typically studying thousands of cyclists and their routes. The first of these studies, conducted in Zürich (Menghini et al., 2010), analysed nearly 2500 journeys from over 2400 cyclists. The sample size allowed the creation of a route choice model, but, since this research did not collect any data associated with the cyclists or the trips, disaggregation by individual and important features of the street network (such as slope or traffic) were omitted in the model.

The sample analysed in Zürich was obtained from an independent GPS study that collected raw GPS data from nearly 5,000 participants carrying a GPS receiver for up to a week, resulting in over 32 000 trips in the cities of Zürich, Winterthur and Genève. The raw data was processed to identify different transport modes and trips (Schuessler & Axhausen, 2009b), extracting cycle journeys for independent analysis. Modes were detected based on the average and maximum speed during the trip, or by investigating vicinity to infrastructure and stations/stops during the trip. In the latter case, geo-data regarding stops and infrastructure was linked to the GPS data using Geographic Information Systems (GIS). For instance, Stopher et al. (2008) first extract walking trips, followed by public transport trips. Of the remaining trips, bicycle trips were extracted based on speed and acceleration characteristics. They comment that GPS loggers can be configured such that they will not record when stationary (to save the battery). However, when the respondent starts moving again the logger needs some time (up to a few minutes) to locate its position, potentially leading to missing trip starts, which requires additional pre-processing. Broach, Dill & Gliebe (2011, 2012) developed a route choice model from GPS data collected in Portland, Oregon, focussing on the journeys of regularly commuting cyclists. This was a smaller study (with only 164 subjects and around 1500 trips), but its small scale allowed the research team to collect more detailed demographic data via questionnaire – recognising that cyclists are a heterogeneous community whose route choices might vary significantly.

At approximately the same time, in Los Angeles, Reddy et al. (2010) had carried out the first study using smartphones as a mechanism for collecting GPS data. With the aim of building a platform that enriched the route sharing process, the *Biketastic* project developed a mobile application for Android phone users and distributed it online for free, recruiting 450 users (Savage, 2010). The project website allowed participants not only to visualise and manage their trips and statistics, but also to share their routes, and visualise other cyclist's journeys and other data. GPS data was associated with noise level and roughness data collected through the smartphones' microphones and accelerometers. Volunteers could also provide information about the route as well as uploading photos and videos of the journeys – acting as a community resource, but also providing contextual data for researchers.

Similar schemes followed in San Francisco, California (Hood et al., 2011), and Austin, Texas (J. G. Hudson, Duthie, Rathod, Larsen, & Meyer, 2012). The first of these used the mobile application *CycleTrack,* developed for the study by Charlton, Schwartz, Paul, Sall, & Hood (2010) and made available for Android and Apple iOS in an effort to broaden the volunteer base. The initiative collected the largest sample of cycle GPS tracks to date for research purposes, with nearly one thousand volunteers contributing data over a five-month period. Through the app, volunteers provided data about their gender, age and travel purpose, which were incorporated into the route choice model. Unfortunately, fewer than one third of these journeys were successfully mapped to the road network for further analysis. This cleaning and map-matching processing was improved by the research conducted shortly afterwards using the same GPS smartphone application in Austin, Texas (J. G. Hudson et al., 2012). Although a smaller study, they succeeded in matching a similar number of routes. In both of these studies, the participants were recruited from the smartphone users community, raising the question of sample bias; however, comparing demographic data from the smartphone study with information obtained from local travel surveys did not reveal significant difference in mean age, although they did reveal a gender bias towards males in the smartphone study. Other socio-demographic data, such as income, were not collected to avoid private concerns. Smartphone ownership might have a skew in that regard, but it has not been possible to test this.

Following these pioneering studies, more recent research initiatives have focussed on smartphone GPS applications, improving the online platforms and websites that link apps with volunteers, and providing new functionalities to encourage people to participate. The initiative *Madrid cycle track* (Romanillos, 2013; 2014) engaged three hundred casual bikers, as well as cyclists for bike-messenger companies. The initiative collected over 45 000 km of GPS tracks through a free mobile application, *Map My Tracks*. In an effort to broaden the user base, those without smartphones had the option of drawing their routes on an online map. In both cases, associated information about the age and gender of participants and the purpose of the travel was collected. It was also the first initiative to allow volunteers to visualise the whole network of collected tracks on a single online map.

In the Netherlands, a similar community-focussed initiative was created to generate interest in pedelecs (electric bicycles). *B-Riders* in Noord-Brabant in the Netherlands started in September 2013 and ended December 2014, with the aim of shifting users from car travel to pedelec use. Participants could either register for a financial compensation -from €0.10 to €0.15 for each kilometre registered in the morning or the evening peak hours, with a limit of €1,000 for each participant, or register for a coaching program with feedback and encouragement on their individual behaviour, or both. To receive the financial compensation and the feedback, participants were obliged to make use of a smartphone GPS application developed for the program – resulting in an unprecedented 400 000 GPS tracks collected over the period. Bike Print (2014), which allows visualisation and summary of the data by users (such as specific length of the trip), was developed specifically for the task, and the data was subsequently used to predict future usage of the bike network (Coevering, Leeuw, Kruijf, & Bussche, 2014).

2.3.2.2 Big GPS Data from “big app” companies

The volume of GPS data collected by studies increased significantly when researchers implemented GPS mobile applications. The development of associated online platforms, and advertising campaigns among the cyclist community, served to engage larger groups of participants. However, the sample of contributors still tends to be small compared to the cycling population in the studied locations. The growth in sports and fitness apps have opened up sampling of huge numbers of users (Evans 2013; Flurry Analytics, 2014). In the US nearly one-third of smartphones owners (46 million people) currently use health or fitness apps (Nielsen, 2014a), aided in part by smart watches and fitness bands (Nielsen, 2014b). These wearable devices are however currently mostly appealing and affordable for a limited group of wealthy young people, and even within this group, two thirds of users do not use these devices for more than six months (Mitesh, Patel, MBA, & Hall, 2015). Among these fitness apps, GPS sports tracking apps have been especially popular. In 2013, 7 of these apps surpassed 16 million downloads (Comstock, 2013); in 2013, the popular *Endomondo* celebrated its fifth birthday and reached 20 million users in more than 200 countries (Endomondo, 2013). *MapMyFitness* experienced an even more rapid expansion, surpassing 20 million members in October 2013 (Map my fitness, 2014). App developers ascribe this popularity to attractiveness of the social dimension of the service as well as the introduction of new features like training plans (Endomondo, 2013). We are living in the era of not only Big Data, but Big Apps.

These apps are widely used by cyclist for tracking sport activities. *Endomondo* has registered almost a billion miles of cycling activities, more than half of the total uploaded (Endomondo, 2013). *MapMyRide*, one of the most popular together with *Strava*, has over 20 million users (Map My Ride, 2014), who have uploaded over 70 million routes (My fitness pal, 2014). *Strava* does not disclose its number of users, but 2.5 million GPS-tracked activities are uploaded to its website every week (Strava, 2014a) and more than 90 million rides have been collected (Albergotti, 2014).

There are limited studies on these new big GPS datasets from app companies. Cintia, Pappalardo & Pedreschi (2013) examined GPS tracks of nearly 30 000 cyclists, collected via the *Strava* API and analysed training performance using average speed, duration of ride and cyclist's heart rate. Wamsley (2014) focussed on analysing travel times collected through Strava in order to generate pacing strategies for a cyclist to complete a course in the fastest time possible. Other research defined the conceptual architecture of data collection, management and methodologies for using and analysing the data (Clarke & Steele, 2011), including data cleaning, visualisation and trajectory clustering techniques (Peixoto and Xie, 2013). Other work has instead focussed on the use, the motivations and the online community experience for the people that use cycling apps (Smith, 2014). Very few researchers in this field have focussed on the analysis of urban transport cycling to improve urban planning and design (Clarke & Steele, 2011) or have developed specific tools to analyse cyclists' routes. Researchers in Reykjavik (Jónasson et al., 2013) have done work in this area, using GPS data from *Garmin Connect* and *Strava* online platforms to create heat map and analyse cyclist route choices .

The research and planning disciplines are traditionally more interested in urban transport cycling and require high data density, and data which is representative of the population in their study region, to build and validate models which big app data does not necessarily provide. This is beginning to change, as *Strava* is the first of these companies to sell cycling GPS data. On May 2014, the company launched *Strava Metro*, a commercial brand of the company focussed on providing data services to local authorities, research institutions, and other interested parties (Strava Metro, 2014a). In 2013 (Maus, 2014), Oregon's Department of Transportation was the first partner to sign with *Strava* (Albergotti, 2014). Other urban planning authorities around the world (including London and Glasgow in the UK, and Victoria in Australia) have followed suit (Albergotti, 2014; Sparkes, 2014). Strava have also launched *Strava Labs*, a high-resolution online map that visualises the cycle flow distribution collected through the app around the world (Strava Labs, 2014), representing over 75 million journeys and 220 billion GPS points (Mach, 2014).

Models like *Strava Metro* bring significant new opportunities for analysis and understanding. First, the *Street map* shows a very high density of GPS tracks covering the whole metropolitan area (although still exhibiting some degree of spatial and sociodemographic bias). The data is processed to remove users' personal information, but summaries of basic demographic information (gender and age ranges) *are* provided, allowing demographic bias to be estimated. Additionally, it provides not only information about the total number of cycle trips but also the number of commuting trips - very important information for urban transport planning. *Strava Metro* also provides cyclist flow information at different dates and times – e.g. via the *Strava Saturday* online heat map (Strava, 2014b)- so it is possible to analyse cyclist flow for different times of the day (the morning and the afternoon peaks), and study the evolution across the whole year, opening up the possibility of detailed spatiotemporal and seasonal analyses.

However, *Strava Metro* data also presents limitations. Users' privacy concerns mean that single route tracks are typically not accessible so it's not possible to analyse trip length, purpose of travel or the route choice on an individual journey level. Because this data is shared in an aggregated form, it is not possible to study the relationships between these variables; for example, the dependence of route choice on the cyclist's travel purpose. Because we only have aggregated socio-demographic information, there is limited scope to analyse the importance of basic factors like age or gender in route planning, journey length or purpose. All of these analyses are likely to be important for planning, designing and managing cycle infrastructure. The solution would be to have access to disaggregate data and provide single tracks, a difficult proposition when maintaining user (and company) privacy. In order to not discourage user participation, shortly after opening *Strava Metro*, the company offered members the option of marking routes as private – these routes are then not included in *Strava Metro* dataset (Wehner, 2014).

2.3.3 Research focused on point data

As well as the substantial body of research around GPS, there has been a significant interest in analysing cycling data gathered at specific locations. Studies have mainly explored two different data sources: point data registered at Bike Share Programmes (BSP) stations and counts.

2.3.3.1 Exploring Bike Share Programmes data mines

With the exception of studies based on bike parking data provided by specific, one-off surveys (Rietveld, 2000), bike mobility trends have not been analysed through large point datasets gathered at BSP docking stations or parking lots - until recently. The biggest evolution in this area came with the rapid expansion of BSP in cities around the world. The *first generation* of such systems date from 1965 (Demaio, 2009), but they remained very few and small in size till the early-1990s, when a *second generation* of BSP was born. Still these programs grew slowly until the mid-2000s, when a *third generation* of bike share (characterised by electronic management, and hence a rich data source) became popular in many countries. Since then, the number of such systems increased exponentially around the world (Fishman et al., 2013). By the end of 2007 there were about 60 cities with third generation BSP implemented worldwide (Demaio, 2007); according to Fishman (2015) the current number of BSP is 855, with nearly one million bicycles in use.

A common feature of this third generation of BSP is that they record information when a bike in undocked (hired) or docked (returned). This data was first explored in a study in the Barcelona BSP, *Bicing* (Froehlich et al., 2009), covering August to December 2008. Three different kinds of data were gathered from the *Bicing* information system by scraping the website (using an automated program to find and store the relevant data elements presented by the webpage). This data was collected every two minutes and included the station locations, the number of available bicycles, and the number of vacant parking slots. *Bicing* launched in 2007; it had nearly 400 stations and 6,000 bikes, with 150 000 subscribers. Firstly, by applying clustering techniques, the research identified spatiotemporal patterns, relating the use of different bike stations to activity clusters over the course of a weekday, when more regular BSP usage patterns were identified. Secondly, the research developed different predictive models to analyse the impact of several factors (such as time of the day or the amount of historical data) in order to create tools to estimate bicycle demand for different stations and the optimal location of future ones. The research pointed towards the potential of this new source of data to identify not only cycling or mobility patterns, but broader urban trends and dynamics, such as inferring urban land uses (home, office or leisure/retail) by analysing users' profile over time.

A later study worked with Barcelona BSP data with more specific objectives (Kaltenbrunner, Meza, Grivolla, Codina, & Banchs, 2010). Aware that users of *Bicing* often found it difficult to find a bike to hire, or a space to leave their bike at their destination, the researchers developed a model that could predict the availability of bikes or docks, and could inform both users and system managers in advance so that they could respond accordingly. Even an hour ahead, their autoregressive–moving-average (ARMA) model was typically accurate to one bicycle, representing a usable prediction range for cyclists. More recently, Giot & Cherrier (2014) completed a similar predictive analysis based on Washington, D.C. BSP data, working with a suite of research regression techniques.

There has been a range of effort to work with BSP data in real time, building new tools for system management and to improve service. In 2009 Luo & Shen (2009) developed an information system for the BSP of Hangzhou (China) that represented the location of the BSP stations and dynamically displayed the availability of bikes or free parking spots. The most remarkable visualisation of real time BSP information is *The Bike Share Map* (O'Brien, 2010; 2013). Created in 2010 in order to visualise London's BSP data, the map represents the information of different cities around the globe since June 2013, covering at time of writing 107 BSP and visualising the availability of systems around the world. This global view was incorporated into research based on BSP data (Cheshire & O'Brien, 2013; O'Brien et al., 2013). The investigation collected data from 38 systems from Europe, the Middle East, Asia, Australia and America, and the dataset included locations, capacity and current load factor of docking stations. After analysing the data, the investigation compared and classified the BSP according to variables such as the system's geographical size, the variation of occupancy rates across the day or the week, and the intensity and distribution of activity in relation to demographics. The paper compared the geographical distribution and temporal popularity of a range of different schemes, allowing planners to examine schemes with elements in common in other parts of the world.

As well as research focussing on providing useful apps and interfaces to service providers, researchers are increasingly taking more theoretical approaches to dock data to understand differing spatiotemporal patterns using signal processing and statistical methods. In 2012, Lathia, Ahmed and Capra, (2012) used cluster analysis to detect "similar" stations in the London system based on the time profile of their occupation, resulting in docking stations which have similar behaviours over the course of a day, and examining the impact of "casual" users. These users pay using a credit card instead of the access keys used by subscription users at the time of the programme's launch - these casual users may be more likely to be tourists or business visitors. Similar methods were applied by Côme & Latifa (2012) to cluster docking stations which are similar in their temporal patterns of occupation, focussing on the flagship *Velib'* system in Paris. This covered 2.5 million trips in just one month - *Velib'* is the second largest BSP in the world. Working on the London system, Padgham (2012) is one of the first to attempt to connect BSP activity with that of the other parts of the public transport network, and introduced spatial interaction model-like approaches to understanding flows between locations. Many of these studies focussed on Europe and North America. Corcoran, Rohde, Charles-Edwards & Mateo-Babiano (2014) studies Brisbane, Australia and examines the impacts of weather and public events on city cycle use. In Melbourne, Fishman, Washington, Haworth and Mazzei (2015) used data collected from BSP trips in 2012 to visually represent the strength of the relationship between different docking stations and how this relates to the public transport system

Research on point data in BSP systems has yielded a raft of visualisations, apps and analyses. Many of the more academic works have employed specialised statistical techniques that are perhaps not as familiar to the policymaker or transport planner, and joining up the scientific expertise with services and interventions amenable to the user, service provider or policymaker still has a way to go. Limited work has been done to combine it with journey data, which in itself would yield new possibilities.

2.3.3.2 Other point data sources: Manual and automated counts

While BSP provides detailed and timely point data reporting, there are other sources that provide large and useful point data collections, but rarely on the same scale and level of detail. Within the scope of this review, the evolution of counts in the last years is especially interesting.

Though manual counts cannot be considered as a source of Big Data – they just meet the first V criterion (volume) of Laney's (2001) classification - they are still the most prevalent cycling data collection method (Ryus, Laustsen, Proulx, Schneider, & Hull, 2014), producing increasingly large datasets through recent initiatives. Many communities still successfully use conventional, lower-tech methods in order to collect point data and support an evidence base for cycling policy. In some countries, like the US, many cycling communities (Schneider, Patten, & Toole, 2005) encourage volunteers to register cyclists at key locations in precise dates through manual count methods. Among the different initiatives, especially remarkable is the *National Bicycle and Pedestrian Documentation Project* (NBPD, 2009-2015), a program that provides to the volunteers a methodology, as well as training and documentation, and centralises the collection of surveys and counts from cities all around the US.

Apart from these massive manual counts initiatives, there is a substantial collection of cycling data through automated counts. The most common methods are based on pneumatic tubes, inductive loops, passive infrared, automated video counters, infrared cameras and fibre optic pressure sensors (Ryus et al., 2014). Pneumatic and inductive are widespread, but proved to be accurate only when detectors are properly installed, calibrated, maintained, free of external interference, and on a dedicated bicycle lane (Nordback & Janson, 2010). Recently, more innovative counts based on fibre optics register cyclists on mixed traffic lanes, offering insight not only in the cycling volume but also in the speed and direction. In the Netherlands, new traffic light detection loops have been implemented to detect cyclists with high accuracy by using a new methodology with dedicated algorithms (Winter, 2012; Rijn, 2014). This system is being implemented extensively in some cities: Utrecht is currently adjusting 170 traffic lights which measure motorised traffic to also detect cyclists. This cycling data is being made available in an online open data platform (Open Data Utrecht, 2015). Such efforts could be facilitated by the technological innovators who are working to create sensors which cost close to $50 – 1% of the cost of current sensors (Andersen, 2015). *Knock Software* is one such innovator, active in Portland, OR on a device which uses magnetic, thermal and speed detection to determine whether a passing object is a bike, a car or a pedestrian. If this proves reliable, coverage of cities could rapidly become more comprehensive, detailed and timely.

Considering that count data is at the base of many studies which examine travel patterns, it is worthy to highlight the most important advantages and disadvantages in relation to other approaches. Count data register every single cyclist at a specific location while BSP or GPS data relies on a more segregated cycling population. However, the absence of sample bias in count data is not guaranteed at all, and it is collected on an aggregate level such that no demographic data is captured. According to Ryus et al. (2014), manual counting is still the most dominant method of counting cyclists - 87% of total counts in the US - and still relies heavily on volunteers. That means that samples are usually registered at a limited number of locations in a specific date or period of time, and may have spatial bias if the count locations are not well distributed. The increasing extension of new automated counts could allow pattern analysis across time - and, if well distributed, could reduce spatial biases.

2.3.4 Research focused on journey data from Bike Share Programmes

The third generation of BSP not only record information about the number of bicycles in docking stations, but also identify and register bikes (and sometimes an identifier for their users) at the start and end dock of every journey. This means that BSP are able to provide general mobility data through the origin-destination matrices associated with users', but also timings of these journeys (and, by inference, duration). In addition, BSP may provide data about cyclists (age or gender, for instance) – although this is not always the case, either because the data is not collected (from casual, credit card users), or because that aspect of the data is withheld for privacy reasons. Research on journey data has so far been more limited. BSP journey data is historical; it is typically released in large batches covering months or even years of activity. It has limited use for nowcasting or feeding back information to users in real time. Nevertheless, there has been significant work in visualising this data (Wood, 2011; Zaltz Austwick et al., 2013; Bargar, Gupta, Gupta, & Ma, 2014), creating a comparison study of different visualisation techniques with respect to this data.

The research carried out by Borgnat et al. (2011) is one of the first analytical approaches to these origin-destination datasets, and focussing on data from the city of Lyon in France. The investigation analysed the dataset provided by the managing company and the City Hall, corresponding to the 13 million trips over a two and half year period. The system registered the start time and departure station, and end time and destination station, for each journey. For the first time, researchers could examine individual mobility, characterising different groups according to the distance, duration or speed of their trip. While the research carried out in Barcelona on point data (Froehlich et al., 2009), covered a short period of time, the research conducted in Lyon allowed trend and temporal analysis over a much longer period. The data collection began at the opening of the system and covered expansions of the scheme, allowing the study to cover different demand and service scenarios throughout this period, and analysed how factors such as increasing numbers of bicycles and stations affected the number of subscribers. The same year, Vogel, Greiser, & Mattfeld (2011) analysed similar data from Vienna's BSP, *Citibike Wien*, covering around 760 000 rides from 2008 and 2009. General spatio-temporal patterns are derived from the analysis while an integrated approach of Data Mining and Operation Research is presented in order to develop a new trip model that anticipates bike activities for better long-term location planning. The researchers were able to formulate clear policy goals from their analyses.

The first multi-city analysis of origin-destination data was carried out by Zaltz Austwick et al. (2013), which compared five cities (London, Washington DC, Minneapolis, Denver and Boston), using spatial network analysis methods to cluster stations into communities (subnetworks of journeys within the wider network). The smallest of these datasets covered 168 000 journeys (Denver) and the largest 3.6 million (London) and allowed comparison of distance travelled and journey time distributions between cities. The paper also used inferred routing for visualisation purposes using Open Street Map and Routino (http://routino.org), but did not utilise this for distance estimation or street network loading, as there was no mechanism to validate this route choice. Bargar et al. (2014) builds on a network analysis approach (examining data from Washington DC, Chicago and Boston), complementing it with the spatiotemporal clustering methods used by other researchers, and visualising both of these techniques via a web-based map visualisation built using JavaScript libraries, integrating analysis into a more accessible visualisation tool.

More recent work has expanded its scope beyond predicting demand or detecting similar locations, and has focussed instead on correlating cycling activities with wider policy goals around health and transport. The use of the London BSP across the three first years of operation have been examined by Goodman & Cheshire (2014). The study analysed the evolution in the profile of users, the increase in the number of trips as well as variation in the proportion of trips by registered users. This covered a period of time that included the extension of the BSP network in 2012 and the rise of the service prices in January 2013. The dataset incorporated the gender and home postcodes of users, permitting analyses that linked geographic socio-economic factors of the residential locations, and evaluating the demand according to the distance from homes to the start or end stations. Defined as "trips made by two or more cyclists together in space and time" data (Beecham & Wood, 2014, p.1), group-cycling journeys on London BSP were studied by analysing the trips of over 80 000 members between September 2011 and September 2012. The research revealed some plausible patterns, like the increase of group cycling journeys at weekends, late evenings and lunchtimes, and the large proportion of group members that share the same postal code. However, it also revealed some unexpected ones, like sets of commuting group cycling journeys, and some differences between group and individual trips according to gender. This simple approach starts to connect BSP work with wider interests around social behaviour, health and leisure. Faghih-Imani, Eluru, El-Geneidy, Rabbat, & Haq (2014) studied how land use, urban form, building environment attributes and weather impact on the bicycle flow, by analysing the data from the Montreal BSP, *BIXI*, between April and August 2012. The research reports, unsurprisingly, good weather leading to high cycling flow, but also provide interesting findings for policy makers and urban designers, such as the relationship between BSP usage and urban density, and the interaction between cycling and public transport.

An underused aspect of journey data is its capability to act as a supplementary and validating data source for the more current, accessible point data (which through APIs, is typically updated on a minute-by-minute basis). Point data typically registers only net changes – so, for example, three bikes arriving and two bikes leaving appears the same way as one bike leaving. By using journey data to validate the behaviour of the system, it could be used to infer expected traffic at docking stations (and hence whether a small net change represents large or small flows), as well as allowing spatial models for predicting flows based on just the total ins and outs of each docking station (in GIS, interpolating a matrix from its marginal sums is a relatively standard technique (Deming, 1940)).

Future work on BSP will surely rely on combining different strands of data from within the scheme, or with external datasets. If BSP utilise GPS tracking more widely, it could open up the possibility of a linking of journey data (time-varying origin-destination matrices), point data (station locations and statuses) and routing data (the details of the route that users take between origin and destination on the street network) – allowing inference of time-dependent BSP traffic on the level of individual road segments. If GPS data yields route preference, and journey data yield time-dependent demand at an origin-destination level, combining both with live point data could yield a complex, timely modelling tool. This BSP “nowcasting” could allow prediction in very small time windows – for example, docking station-level occupation and demand in ten or twenty minutes in the future. Combining BSP data with complementary sources – health and demographic data, for example – opens up the possibility to linking BSP to a wider context – including transport planning, access to services of marginalised groups, and behaviour change.

2.4 Recent planning and policy practices, and existing programmes and initiatives

2.4.1 Recent planning and policy practices

Planning and policy practices aimed at fostering cycling mobility, essentially started to be in a new public agenda aimed at shifting towards a more sustainable transport model in the 1970s (Schimek, 1997) and, since then, they have been analysed by an important number of studies, with seminal titles such as “Bicycle transit: its planning and design” (Balshone, Deering, & McCarl, 1975) or “The bicycle planning book”, written by M. Hudson (1978). Just a few years later, this author also led one of the first extensive studies, titled “Bicycle Planning: Policy and Practice” (M. Hudson, Levy, Nicholson, Macrory, & Snelson, 1982), focused on analysing a wide range of aspects: plans for cycle networks and cycling safety, techniques on how to measure cycle usage, it also studied the layout of cycle routes, including aspects such as signing and parking facilities, policies on cycling education and enforcement and finally, it analysed the legal aspects of cycle provision.

Focussing on more recent practices, the study conducted by Pucher, Dill, & Handy (2010), provides an extensive review on the effects of different interventions, based on the in-depth analysis of 139 studies and collecting data from 14 case study cities where multiple interventions were adopted. The study offers evidences that support the crucial role of public policy in encouraging bicycling, and provides a useful classification of the different types of interventions or measures analysed, according to a number of categories. The classification on categories and the most important measures within them are briefly described next:

- **Travel-related infrastructure.** It includes interventions such as road bicycle lanes (usually designated by a white stripe, a bicycle icon on the pavement and signage), shared bus/bike lanes, off-street paths (paved paths separated from motor vehicle traffic), signed bicycle routes (“A shared roadway which has been designated by signing as a preferred route for bicycle use”), bicycle boulevards, cycle tracks (similar to bike lanes, but are physically more separated from motor vehicles, for example with a curb, vehicle parking, or other barriers), coloured lanes (paint or other methods are used to colour bike lanes, making them more visible to motorists), bike boxes (also known as advanced stop lines), bicycle traffic signals, traffic calming, car-free zones, and others.

- **Bike parking and end-of-trip facilities**. It essentially includes: bike parking, showers at workplaces (usually a combination of showers, clothes storage and change facilities) and bicycle stations.

- **Integration of bicycles with public transport**. Facilities such as parking at rail stations, bus stops, bike racks on buses, bike on rail cars (often special space on rail cars reserved for bikes, sometimes with bike racks or hooks, usually permitted during off-peak hours on most suburban rail, metro, and light rail systems in both Europe and North America) or services such as providing short-term rental bikes.

- **Education and training programs**. It includes a variety of programs and courses designed to increase bicycling skills and knowledge of bicycling laws.

- **Bicycle Access Programs.** The most important one is the promotion of **Bicycle Sharing Programs**, but other programs are included, such as giveaways programs, loaner programs, fleet programs and service and repair programs.

- **Other programs and legal interventions to promote bicycling**. General travel programs, trip reduction programs, individualized marketing (comprehensive marketing programs aimed at individuals in a neighbourhood, school, or worksite. Programs usually involve targeted information,) travel awareness programs (a wide variety of programs designed to reduce driving and increase use of transit, walking, and bicycling), safe routes to school programs, *ciclovias* (or *ciclovia recreativa*) programs (free mass recreational programs where streets are temporarily closed to motorized traffic and reserved for se by pedestrians, runners, rollerbladers and cyclists), other specific bicycling programs such as Bike-to-Work Days (which are promotional events that encourage commuters to try to bicycling, usually over a day, a week or a month, usually including free breakfast, giveaways, contests and other activities), or legal interventions such as helmet laws (although mandatory helmet measures have been contested and eventually refused in many countries, such as Spain) or speed motor traffic limitations.

Although the study evaluates the effects of each different measure on the amount of bicycling, independently, the research also highlighted the importance of fostering integrated packages of different complementary interventions, including infrastructure provision, pro-bicycle programs, supportive land use planning and restrictions in car use.

This and other similar studies (Buehler & Dill, 2015; Dill, 2009; Reynolds et al., 2009; Rybarczyk & Wu, 2010) identify the most important types of planning and policy practices being promoted and, usually, describe the positive effects they have on the cycling mobility. However, the discussion about the real effects of the different policies launched in order to promote cycling offers different points of view. On the one hand, the mentioned studies and authors such as Ogilvie et al. (2004) pointed out the positive effects of these policies, especially considering the difficulty of achieving the objective, when stating: “It is difficult to change long- standing and complex patterns of behaviour so the evidence that some in-depth, targeted interventions have achieved any measurable shift is encouraging”, in his review paper “Promoting walking and cycling as an alternative to using cars: systematic review”.

On the other hand, more critical reviews, such as the one provided by Schimek (1997) in *"The dilemmas of bicycle planning"*, or the one coming from Fishman et al. (2013), introduce remarkable warnings and doubts about the real effects of many policies, poiting to many studies in different countries reporting, for instance, that the proportion of car drivers transferring to cycling is not really significant yet. According to them, we cannot assume that a significant proportion of users are transferring to public bicycle from single occupant car use. "Yet, a wide range of papers from a number of countries have reported that this is seldom the case". Other studies support a similar idea; for instance, the United Nations report written by Midgley (2011), warning about the possibility of exaggerating the benefits of many bike share programs, given that it is quite common for the majority of bike share trips to be substituting for sustainable modes. Based on the analysis of data from the Barcelona, Lyon, Montreal and Paris bike share programs, Midgley concludes that these programs show "little impact on reducing car use".

In addition, with regard to this discussion on the real effects utility of certain planning and policy practices, another critical perspective often comes from cycling associations or non-institutional cycling organizations. Against the popularly believed consensus about the necessary development of certain laws (such as the mandatory helmet law) or the implementation of certain facilities, such as bike lanes, some cycling associations hold a contrary opinion, and oppose their implementation (Bravo, 2016) in cities like Madrid, in favour or promoting the coexistence of cycles and motorised traffic on roads through other measures such as traffic restrictions, traffic speed reduction and pro-bicycle policies aimed at arriving to a minimum cycling flow that may guarantee the safety of cyclists as a significant and respected part of the daily traffic on every road.

This thesis may contribute to this open discussion, providing the basis for evaluating the effects that the implementation of different facilities or measures are having in the particular case of Madrid, not only on the levels of cycling activity (through the analysis of the existing cycling flow), as most of the previous studies do, but also on different aspects of cycling mobility, such as the circulating speeds, travel times or the cycling accessibility derived from them. In addition, the "dynamic" analysis of the existing cycling activity at different moments (over the course of the day, during weekends or holidays, for instance), may allow us to evaluate the effects of different measures on certain urban areas at different moments. This is or particular interest in order to evaluate measures such as the streets temporarily closed to motorized traffic and reserved for the use of pedestrians and cyclists, or to identify the areas where this kind of measures would probably have more demand.

2.4.2 Cycling programs and initiatives

The aim of this section is not to provide an extensive review of the large amount and variety of cycling programs and initiatives that are being promoted in different cities all across the world, but to offer a brief overview of the most relevant programmes that are fostering cycling mobility at three different levels: Global programmes, initiatives, projects and programmes promoted in the European context, programmes and organizations at Spanish national level, and finally, the initiatives at municipal level for our case study, Madrid, providing a short description of their mission and their goals.

2.4.3 Global programmes

At a global level, it is remarkable the work developed by United Nations, essentially through three different programs. The first one is the United Nations *HABITAT* Programme, which covers a wide variety of themes. Mobility is one of the aspects UN-Habitat is working in, offering a comprehensive package of knowledge, advocacy, and technical assistance to support national governments and local authorities in the development and implementation of sustainable urban mobility plans and investment strategies. The second one is the United Nations Development Programme (UNDP), which provides some general analysis of mobility and transport, especially in developing countries, and the third one is the United Nations Environment Programme (UNEP), with a specific topic focused on promoting sustainable low emissions transport, with an especial emphasis on walking and cycling.

Although in terms of proposals these programmes may be found too generic, their contribution is relevant, since they provide a necessary global perspective through reports like the recent one published by UNEP, "Global outlook on Walking and Cycling. Policies & realities from around the world" (Jennings, 2016). While most of the existing research on developing cycling mobility focuses on the analysis of European countries, North America and China, the work developed by UNEP, summarised in this report, focuses on low- and middle-income countries that are undergoing rapid, debilitating and unconstrained urbanisation, with cities and rural areas exhibiting poor accessibility and mobility. As stated in the report, in these countries, "cycling is more than low-carbon modes of transport, it is a cheap, flexible, personal mode without which the majority of people in low- and middle-income countries are unable to participate in the economy and community, or access education, health-care and other urban services.

There are other Non-Governmental or Non-Institutional Organizations working to promote cycling globally, such as the Global Biking Initiative (GBI) (https://gbi-event.org/en/) or the Global Cycling Network, but not essentially focussed on urban cycling, but they are not essentially focussed on cycling as an urban transport mode.

2.4.4 European initiatives and programmes

At the European scale, the most relevant efforts in promoting cycling mobility are coming from the European Commission (EC), through a variety of programmes and initiatives. The EC clearly defined its position in the Transport White Paper (European Commission, 2011), by emphasising that walking and cycling should become an integral part of urban mobility and infrastructure design. The EC analyses the current situation on urban transport mobility through initiatives such as the "Eurobarometer survey: attitudes of European towards urban mobility" and by monitoring the evolution of transport trends through other instruments like the "Sustainable Mobility Indicator", a methodology defined within the CITEAIR European project (more info at www.airqualitynow.eu).

In addition to these analytical approaches, the European Commission also offers possible solutions in form proposals of planning and policies to be implemented in order to improve and increase urban cycling mobility. In this sense, one of the most relevant European initiatives on sustainable urban mobility in general but also on cycling y particular, is the CIVITAS initiative (http://civitas.eu/). Through this programme, the EU provides solutions with the aim of fostering a "Cleaner and better transport in cities". In the context of this initiative, the Car-independent Lifestyles Thematic group is centred on

"Activities and solutions promoting walking, cycling, multi-modal travel, car sharing, bike sharing and carpooling". Another relevant programme supporting urban cycling mobility within the European context is the URBACT programme, which for about approximately 15 years has been the European Territorial Cooperation programme aiming to foster sustainable integrated urban development in cities across Europe, with Urban mobility as one the key topics, promoting particular initiatives and actions regarding cycling mobility.

Programmes such as the mentioned URBACT and CIVITAS, along with others such as the European Union's Horizon 2020 research and innovation programme, promote specific projects like the CIVITAS FLOW project, which pursuit more specific goals. In the case of the CIVITAS FLOW project, the aim is to provide an analysis of the policies launched in different European and American cities in order to promote walking and cycling, and the effects derived from them. This analysis has been summarised in a recent report (FLOW Project, 2017) describing 15 Quick Facts to provide cities with evidence of how walking and cycling measures can not only improve conditions for pedestrians and cyclists, but also reduce congestion. The report also highlights some remarkable and revealing facts, with the aim of raising awareness on the importance of cycling mobility: cycle highway network reduced the need for 50,000 car journeys daily in the Ruhr area (Germany); just in London, 8.17 million daily journeys made by motorised modes could be cycled in less than 20 minutes; cycling improvements lead to 45% less car traffic and faster public transport in Copenhagen (Denmark), cycle highway reduced time spent in congestion by 3.8 million hours in The Netherlands.

2.4.5 Spanish national programmes and organizations

The previous international programmes and initiatives usually provide general recommendations as well as useful instruments and tools that help national governments and local authorities implement these measures, but it is in the national and the local context where the main decisions are eventually made, and the programmes and initiatives with more impact are effectively promoted.

In the case of Spain, the legal framework for cycling is provided by the *Directorate-General of Traffic* (DGT), the government department that is responsible for the Spanish transport network. The DGT also publishes guides, such as the recent *"Bicycle's users guide"* (DGT, 2016) to inform about the laws regarding cycling mobility as well to give some recommendations.

Among the most relevant Non-Governmental or Non-Institutional Organizations, we can highlight the *Mesa española de la bicicleta* is probably the most complete cluster of Non-Governmental or Non-Institutional Organization in Spain, including *ConBici* (a large association which integrates other 61 national cycling associations), the *Real Federación Española de Ciclismo* (*The Royal Cyclists' Federation*), the Professional Cyclists Association (ACP), the Red de Cicloturistas (Cyclist Lawyers Network) and the IMBA (Mountain Bikers Association).

Non-Governmental or Non-Institutional Organizations play an active role at the national scale in general and also particularly in Spain, shaping the legal framework in dialogue with governmental departments as the DGT in Madrid. In recent years, this was the case when the pressure of different associations led to government to step back in his plans to draw up and apply a law which would have made the use of the helmet mandatory.

2.4.6 Programmes and initiatives at the municipal scale

Local programmes are the ones that effectively take action on the implementation of infrastructure and most of the policies and measures aimed at promoting urban cycling mobility (although, in many cases, in accordance to national policies and always respecting national legal frameworks).

In the particular case of Madrid, the promotion of public programmes and the shaping of the legal framework for cycling is provided by the *Oficina de la Bici* (Bicycle Bureau), as part of the Subdirección General de Planificación de la Movilidad Urbana Sostenible (*Sustainable Urban Mobility Sub-Directorate*) of the Madrid City Council, in charge, for instance, of developing the *Cycling Mobility Plan for Madrid* (2008) and its recent update (2016). More details about this plan, and about public programmes and initiatives will be provided in the presentation of Madrid as the thesis case study.

Again, at this local level, the role of Non-Governmental or Non-Institutional Organizations is crucial, since they cyclists are a quite active collective in general and particularly in the case of Madrid, where the levels of cycling activity are really low even compared to other Spanish cities, and cyclists in general feel the need of pushing the government to take action on it. A recent example that illustrate this constant dialogue is the document that includes all the Suggestions and contributions to the Madrid Cycling Mobility Plan draft (Ayuntamiento de Madrid, 2016) or the collaboration between the Madrid City Council S*ustainable Urban Mobility Sub-Directorate* and different cycling associations when planning the extension of the Madrid Bike Share System (Madrid, 2017).

The different local programmers, plans and policies promoted at this municipal level, will be analysed and discussed more in detail in the presentation of the case study.

This thesis can be particularly useful for the case of Madrid, because of the information collected and the analyses carried out. The distribution of cycling flow across the city network could be analysed with regard to the infrastructure and the measures promoted by the Madrid Cycling Mobility Plan, and in consequence the effects of these measures could be evaluated. It can be particularly useful in the current moment, when new measures will be promoted according to the recently updated Madrid Cycling Mobility Plan. Keep on monitoring casual cyclists' routes as well as BiciMAD users' ones would provide the necessary data for evaluating pre and post scenarios.

2.5 Conclusions

2.5.1 Conclusions regarding current research approaches

As research on cycling mobility has grown over the last years, it has inevitability become more and more specialized. Our classification in different research lines was done just with the aim of organizing better a panoramic overview or current studies, as comprehensive as possible, but it actually portrays this increasing specialization trend, since most of the studies included follow one specific research line (or essentially contribute to one of these lines) and they could hardly be place in a different one.

On the one hand, this specialization is being clearly positive, and the results and advances obtained in each research line evidence a significant improvement. For instance, current route choice studies overcome the traditional SP and RP limitations in terms of high costs, small samples and spatial imprecision (Hood et al., 2011), and the new models developed are improving the understanding of urban cyclist behaviour and producing outputs to inform the planning and design of bike infrastructures and policies.

On the other hand, these specialized studies are often, because of their own nature and aim, too focussed on one single aspect of cycling mobility, so the results obtained are sometimes similarly too particular or specific to be easily considered by policy makers or urban planners, or even technicians.

Although this specialization trend will probably continue over the next years, in parallel and thanks to the increasing availability of new data sources, other studies –such as this thesis– could be considered as cross-cutting studies, since the have started to provide contributions to several research lines at the same time. Even in the cases when they do not provide contributions leading to profound changes in the understanding or a particular topic, their value is to build connections between these research lines, eventually leading to more comprehensive models or tools.

2.5.2 Conclusions regarding research based on new data sources

Section 2.3 reviews the recent bike mobility research based on the analysis of Big Data collected from sources that are becoming increasingly accessible to researchers and policy makers, offering a panoramic view on the growing number of studies that, in less than ten years, have evolved as quickly as the data itself. Even if the achievements are remarkable, there are still important limitations that are difficult to overcome using current data sources. By some estimates, cycling data meets the first of Laney's (2001) "3Vs" classification of Big Data (that of volume), given the size GPS and BSP data, and perhaps the second criterion (Velocity), since some data is available in real time (Luo & Shen, 2009; O'Brien, 2010, 2013). It is more questionable whether the other V criteria (Variety and Veracity) are met, at least in the way that the data is currently being used. In the context of cycling, while the data is combined with demographic or interview data, pooling it with Big Data from other sources seldom occurs. As hinted, there may be scope within BSP to combine point data (sparse, complete and real-time data) with journey data (more detailed, complete and historical samples) and GPS data (very detailed but potentially smaller samples, and historical) to leverage the detail of one dataset against the timeliness and sampling power of the others.

With respect to Veracity, our conclusions differ between sources; this criterion refers to possible biases, noise or any abnormality in data, which is variable for each of the data types. Research based on dedicated GPS data collections have typically paid attention to proper sampling procedures, so that the collected data is by and large representative for the population studied. However, data from big app companies rely on volunteers uploading their cycling tracks, leading to self-selective samples. For instance, logging bike trips in Strava may be more likely to be carried out by cycling enthusiasts who wish to show off their cycling achievements. This would imply a lack of representativeness of the population in terms of cycling attitude, geographical location and socio-demographic characteristics. Groups with mobility impairments, those who are "afraid to cycle", elderly cyclists, or children may not be well-represented in these accounts. Recent studies by Buck (2013a) and Dill and McNeil (2013) demonstrate that heterogeneity along these lines indeed exists, suggesting that data from big app sources will be biased. However, BSP point and journey data is representative, at least of users of BSP. How representative this population is of wider cyclists and citizens is, of course, open to question (see Buck et al., (2013b) for further discussion). Indeed, there is no reason to believe that either BSP or big app data provides representative samples of a cities' population of cyclists or potential cyclists.

Another reason to be concerned about data veracity relates to data collection motivation and methods. In cases in which data is collected specifically for academic purposes, it is typically enriched with contextual information (such as socio-demographics, attitudes, spatial context or environment). When data is collected by commercial applications, aimed at providing a service to customers (e.g. Strava, MapMyRide), privacy policies of companies make using this contextual information difficult or impossible. As a consequence, key variables to understanding travel behaviour, such as socio-demographics or purpose of the journey, may be absent. However, the size of the data gathered and its continuity over time potentially allows for analyses not possible on dedicated GPS data (e.g. spatial clustering or the variation of cyclist flow distribution over time), which may deliver useful additional insights. Similarly, BSP data is collected for management rather than research, and lacks socio-demographic context. In any case, BSP may offer a rich database for analysing regularities in patterns of supply and demand as well as longer term structural developments.

On a technical level, GPS accuracy is not an issue which has been completely resolved. Dedicated GPS devices perform better than smartphones GPS (Lindsey, Gorjestani, Hankey, Wang, & Chen, 2013) but their lack of accuracy in some urban areas can mean analysts lack the fine detail to precisely distinguish route choice – one of the main reasons the data is of interest. The Galileo European Program, which is expected to be in place by 2019 (European Commission, 2014), promises improvements over the current system, but these improvements have yet to be fully demonstrated. For users, one barrier is that, historically, GPS apps have rapidly drained their smartphone batteries – this is significant enough that the *B-Riders* scheme developed an app for an intelligent start and end of the GPS tracking to minimise this problem.

Despite these caveats, there are interesting research challenges and opportunities from the increasing availability of new datasets and the steady improvements in their quality. The industries around sport-tracking apps have seen increases in the number of users of GPS devices (including recent wearable devices) (Nielsen, 2014a). If this trend continues, the volume of data will increase with the userbase, and, through licensing schemes, so will the availability of data. Data from BSP will likely grow, due to the proliferation of BSP around the world. Future research will have to face the challenge of bias in its data collections, and create robust, scalable mechanisms to account for it. We expect more GPS data to become available in a more timely fashion, not only from app companies (some of which are already offering this service for users, like Map My Tracks) but from the current third generation of BSP. Some systems will soon start recording GPS tracks for every journey, which will allow researchers to analyse bike routes and improve the existing route choice and cycling flow distribution models, as well as analyse the real use of existing bike infrastructure.

Apart from these improvements regarding raw location data, work is needed to enrich these data with meaningful explanatory variables. Socio-demographic data may be approximated by linking location data to usage patterns of specific groups. More work will also be needed on data fusion techniques in order accommodate such approximations; however, data providing spatial context (such as land use) is becoming increasingly accurate and more freely available. This growth in bicycle data and its corresponding availability, and joining up with data on transport, health, air quality, demographics, route choice and leisure promises a rich period of activity for researchers in all of these areas.

2.5.3 Conclusions regarding recent planning and policy practices

In a similar way to what has been previously described with respect to research on cycling mobility, recent planning and policy practises aimed at increasing such mobility in cities have been essentially focussed on increasing and improving a number of independent interventions. The effects of such interventions, well reviewed by the in-depth analysis conducted by Pucher, Dill, & Handy (2010), previously described, have been, with more or less effectiveness, clearly positive. However, this study also highlights the importance of fostering integrated packages of complementary interventions, including infrastructure provision, pro-bicycle programs, supportive land use planning and restrictions in car use.

Cross-cutting studies, such as this thesis, may contribute to define more comprehensive measures and policies, thanks to the perspective that it provides on different topics, such as cycling accessibility, cycling competitiveness according to travel times and with respect to other transport modes, or the fact of considering different types of cyclists (casual cyclists, bike-messengers and Bike-Share System users).

Finally, a key question remains: how will the expected advances of research based on new data sources benefit cyclists and potential cyclists, policy makers and BSP? And how would those benefits create wider impacts? Will they encourage more people to cycle, or reduce congestion or pollution? Many BSP users currently take advantage of real time information about the availability of bicycles in different docking stations so that they can plan their journeys. In a near future, we might imagine a smart bike route planning system, integrated in a multimodal transport system. Users will have information about the closest available station to their destination point, and about the best route possible for getting there, incorporating weather, traffic, and user preference – lowering barriers to cycling for less confident or experienced cyclists. Cycling Apps will continue to be attractive to users of smartphones and perhaps a new generation of wearable technology, providing information to cyclists and reports of their peers' performance, motivating people to cycle longer, faster, and of course, more frequent.

For policy makers, the range of benefits may be more diverse. GPS based cycling data will provide insights about cyclists' route choice behaviour and their preferred and disliked route characteristics, which will support the design of cycling infrastructure networks. Coupling GPS based cycling data with geo-data (land use, facilities, altitudes, etc.) will greatly enhance their understanding of cyclists' route choice. Big Data will drive the assessment of cycling infrastructure at different levels, analysing the use of local infrastructures (such as lanes or bike parking), identifying the main cycling routes over the course of a day, or understanding the obstacles, delays and dangers that slow or hinder their journeys. Again, a key issue here is the representativeness of the pool of GPS users. While an initiative such as the Dutch *BikePRINT* project delivers useful insights in cycling routes and cycling densities, it relies on voluntary participants, leaving questions about reliability of the outcomes (Coevering et al., 2014).

The recent collaboration between commercial Apps and planning institutions is promising and will generate combined and useful information that will make new explorations possible. As we have remarked, these new Big Data will not substitute but complement other more conventional sources, since they often lack disaggregate data on the cyclists, which are so often necessary to understanding the contexts that influence many of their decisions. This points, then, to a future where the fourth V – Variety – creates new innovations and insights in cycling – as Big App data, real-time BSP feeds, and more traditional, detailed, demographic studies are brought together – and commercial, municipal, service provision and academic partners work together to create a living, user-centred picture of the cyclable city.

3 Madrid as a case study

3.1 Introduction to the case study

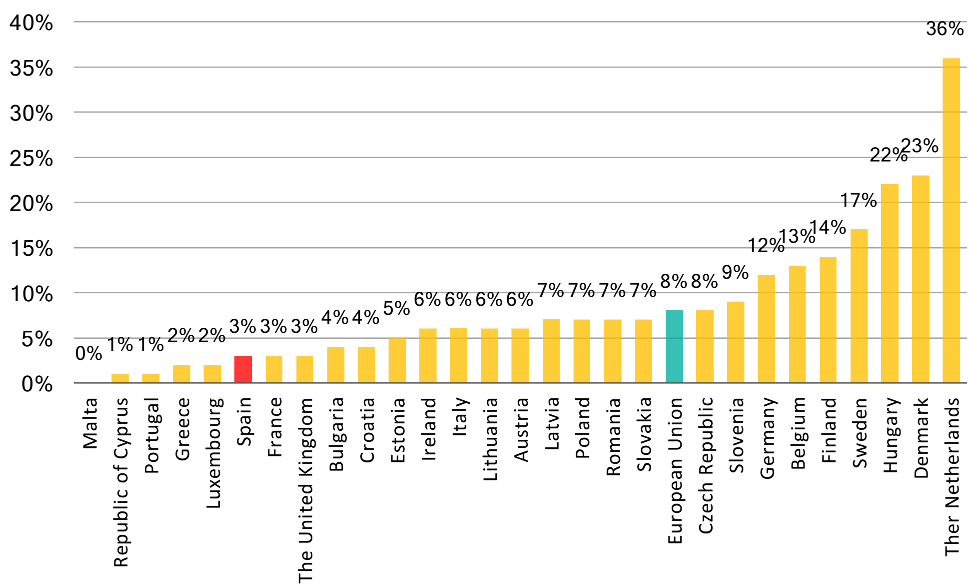
This section introduces the thesis case study, the city of Madrid, describing different aspects about the existing cycling mobility and providing a framework to understand the different analysis performed and the results obtained. It portrays the most important cycling mobility patters, introduce the role and impact of the relatively recent and rapidly growing Bike Share System (BiciMAD), and finally, it describes the existing cycling infrastructure and current policies and plans.

3.2 General mobility patterns and cycling culture in Madrid

Spain is one of the countries with highest levels of public transport use (European DG MOVE, 2014), and Madrid presents not only an important public transport use but also a relevant share of non-motorised transport. According to the last Mobility Survey conducted in Madrid (Consorcio Regional de Tranpsortes de la Comunidad de Madrid, 2014), public and private transport account for the 53.2% and 43.1% of the trips respectively (another 3.7% apparently correspond to other modes), and motorised and non-motorised transport correspond to the 75.4% and 24.6% of the trips respectively (with a remarkable positive different of 8.74% in 10 years).

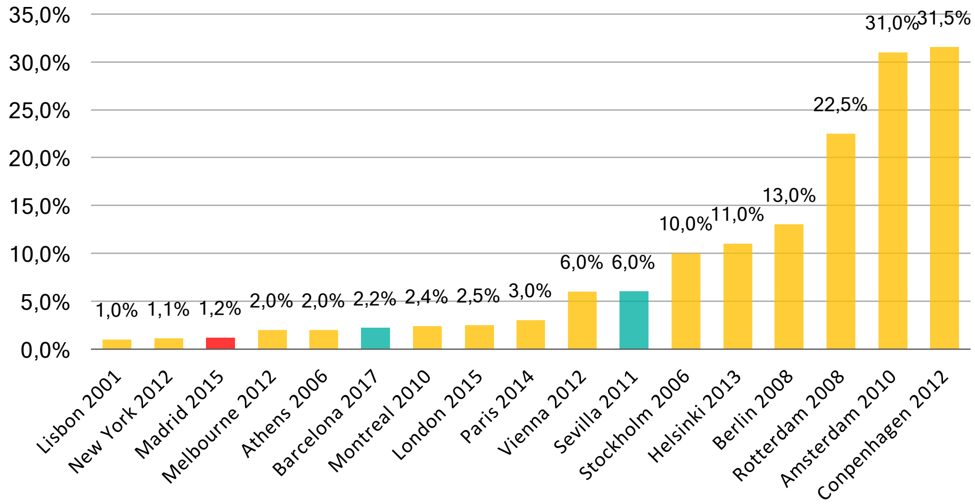
However, Spain shows low levels of cycling mobility compared to other countries of the European Union, as Figure 3.1 shows, illustrating the data obtained from the Special Eurobarometer 422a "Quality of transport" (European DG MOVE, 2014), on the cycling modal share of the 28 countries of the European Union, on a typical day. Spain reach a 3%, similar to the modal share of France or The United Kingdom, but far from the European average (8%) and of course from the countries with highest levels of cycling activity, as The Netherlands (36%) or Denmark (23%).

Figure 3.1: Cycling modal shares in the EU (Eurobarometer, 2014)



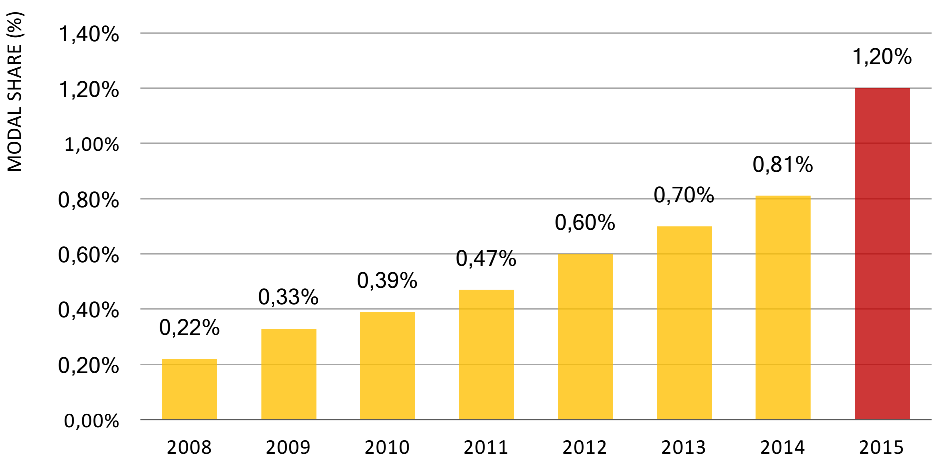
The analysis of cycling modal share in the particular case of Madrid evidences an even lower value. Cycling culture is relatively low, (Muñoz, Monzon, & Lois, 2013), as the comparison of the cycling modal share in Madrid and other cities reveals (Figure 3.2), considering other sources (Blanchar, 2017; Buehler & Pucher, 2012; Future, 2014; MacMichael, 2014; Marqués & Resumen, 2011; Transport for London, 2015). With a cycling modal share of 1.20%, Madrid is far from the modal share reached in other cities such as Berlin (13%), of course Copenhagen (31.5%) or Amsterdam (31%) but also with regard to other Spanish large cities such as Barcelona (2.2%) and Seville (6%).

Figure 3.2: Cycling modal share in other locations (2006-2017)



Having said that, Madrid shows a very positive trend, and partially encouraged by the pro-cycling policy measures, policies and infrastructure, implemented by the local government over the last years (Ayuntamiento de Madrid, 2015), cycling mobility has been growing intensely over the decade, as the

Figure 3.3: Evolution of cycling modal share in Madrid

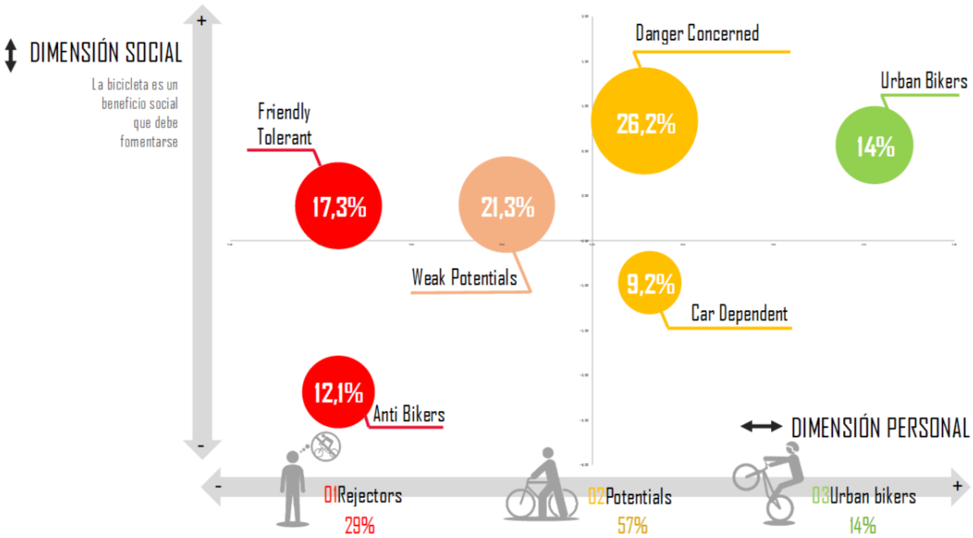


evolution of the cycling modal share over the last years reveals (Figure 3.3), according the data collected from different sources by Kisters, García, Rondinella, & Alduán (2016).

In addition to these general trends on cycling mobility, it is necessary to look into cycling community more in-depth and analyse its socio-demographic profile, with the aim of identifying key characteristics or imbalances that should be taken into account, for planning purposes in general, and for understanding the analysis and results of this research in particular.

According to a recent study (CONECTA, 2015), although a 57% of the population use to cycle with recreational or sportive purposes, just a 14% — sometimes or frequently — use the bicycle as an urban transport mode. A 29% of the population reject its use and a 57% of people are considered as potential cyclists, since they assert they would be willing to cycle in the future, given certain circumstances or conditions. Potential cyclists group present a higher proportion of males and their average age is 37.5, while the group rejecting the use of bicycles presents a high proportion of women (62%) and their average age is 42.4. They essentially argue that cycling is not safe and is not comfortable in Madrid, given the existing conditions. Figure 3.4 illustrates and summarises the results of the study on the attitude towards urban cycling in Madrid conducted by CONECTA (2015).

Figure 3.4: Attitude towards urban cycling in Madrid (CONECTA, 2015)



The question of gender is relevant when analysing the existing cycling community in Spain, since an important imbalance is revealed. According to the report *"Informe de Resultados del Barómetro anual de la bicicleta en España 2015"* (GESOP, 2015), males and females account for the 61,7% and 38,3% of the cyclists respectively, showing a slightly more balanced proportion that in the 2011 report, where the percentage were 63,3% and 36,4% for males and females respectively. The reported average age of cyclists was 38.5.

More dramatic is the gender imbalance in the cycling community of Madrid uncovered by the studies conducted as part of the Cycling Mobility Master Plan or *Plan Director de Movilidad Ciclista de Madrid*

(Ayuntamiento de Madrid, 2008), with the aim of analysing the existing cycling demand (DOYMO, 2011; EUSA Sociología, 2011; Monzon de Cáceres et al., 2011). Table 3.1 shows the results of the counts carried out by these studies, proving information on the proportion of males/females, as well as the percentage of occasional and daily cyclists. The average percentage of cycling males and females is 82% and 18% respectively.

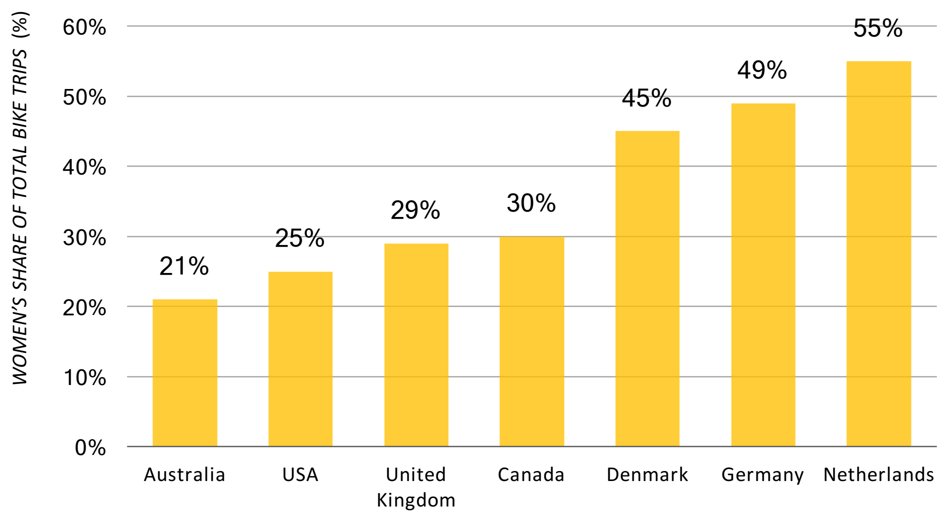
Table 3.1. Cycling counts on different urban areas in Madrid (PDMC, 2011).

Area of analysis	Gender		Use of bicycle		Counts
	Males	Females	Occasional	Daily	
Prado-Recoletos-Castellana	81,0%	19,0%	18,0%	2,4%	2475
Hermanos García Noblejas	83,7%	16,3%	3,33%	0,0%	1433
José del Hierro	78,3%	21,7%	3,9%	2,5%	814
Atocha / Mayor / Alcalá	82,4%	17,6%	3,0%	3,0%	882
Bailén	80,8%	19,2%	3,0%	3,0%	402
Ciudad Universitaria	78,7%	21,3%	20,7%	12,7%	567
Total counts	**82%**	**18%**			**6573**

These results can be compared to the ones offered by different studies conducted in the city of Madrid by diverse cycling associations, based on counts carried out by volunteers. The results shown in the report *"Estadística Bicis Madrid"* (Asociación Pedalibre, 2007), regarding the proportion of cyclists according to gender, are exactly the same as the obtained by the previous studies, with an average percentage of cycling males and females of 82% and 18% respectively.

In any case, these results are not so striking if we consider the existing imbalance the use of bicycle according to gender at an international level, illustrated in Figure 3.5: "Women's share of total bike trips" (Pucher & Buehler, 2008). As the figure shows, in the countries where there is a more important cycling culture, this imbalance is basically inexistent.

Figure 3.5: Women's share - total bike trips (Pucher & Buehler, 2008)



This imbalance in terms of gender is not so extreme when analyzing the willingness to cycling, given a more favorable scenario. The previously mentioned studies conducted as part of the Cycling Mobility Master Plan or *Plan Director de Movilidad Ciclista de Madrid* (Ayuntamiento de Madrid, 2008), carried out a number of surveys at different locations in the city of Madrid with the aim of knowing this willingness and then estimate the potential number of cyclists. The results are shown in Table 3.2.

Table 3.2. Willingness to cycling in Madrid (PDMC, 2011)

Area of Analysis	Willingness to change to cycling mode				Potential change	Counts area
	Willing to change	It's probable	It is not probable	Not willing To change		
Prado-Recoletos-Castellana	30,0%	-	-	70,0%	45,0%	2475
Hermanos García Noblejas	34,8%	32,6%	10,0%	22,6%	67,4%	1433
José del Hierro	37,0%	27,4%	11,0%	24,7%	64,4%	814
Atocha / Mayor / Alcalá	14,0%	35,0%	34,0%	17,0%	49,0%	882
Bailén	23,0%	38,0%	29,0%	10,0%	61,0%	402
Ciudad Universitaria	34,7%	34,7%	16,0%	14,0%	69,3%	567
Average / Total counts					**55,9%**	6573

Focusing on the role of gender in this willingness to cycling, the same studies reveal a more balanced predisposition to change, shown in Table 3.3. These results reveal that the existing imbalance in terms of cycling according to gender is not due to a lack of interest or predisposition, but to the fact that women in general find the current scenario less favorable to cycling than men.

Table 3.3. Willingness to cycling according to gender in Madrid (PDMC, 2011)

Gender	Willing to change	It's probable	It is not probable	Not willing To change	Current percentage	Potential change
Males	16,0%	41,0%	30,0%	14,0%	2,1%	59,1%
Females	19,0%	28,0%	35,0%	17,0%	0,4%	47,4%

Regarding the analysis of the existing cycling community according to age, interesting findings are exposed again by the studies conducted as part of the Cycling Mobility Master Plan (Ayuntamiento de Madrid, 2008). Table 3.4 shows these results, by pointing out the proportion of cyclists that corresponds to different age groups.

Table 3.4. Proportion of cyclists according to age (Barómetro de la bicicleta en España, 2011)

Age group	Daily	One or several times per week	During weekends	One or several times per month	Never or almost never
12-24	28,0%	27,0%	22,9%	28,7%	11,0%
25-39	29,2%	36,9%	39,8%	37,3%	29,5%
40-54	28,8%	24,0%	26,4%	24,9%	30,0%
55-69	13,9%	9,2%	9,6%	6,2%	19,0%
70-79	0,0%	3,0%	1,2%	2,9%	10,5%

3.3 BiciMAD: the emergence of Madrid Bike Share System

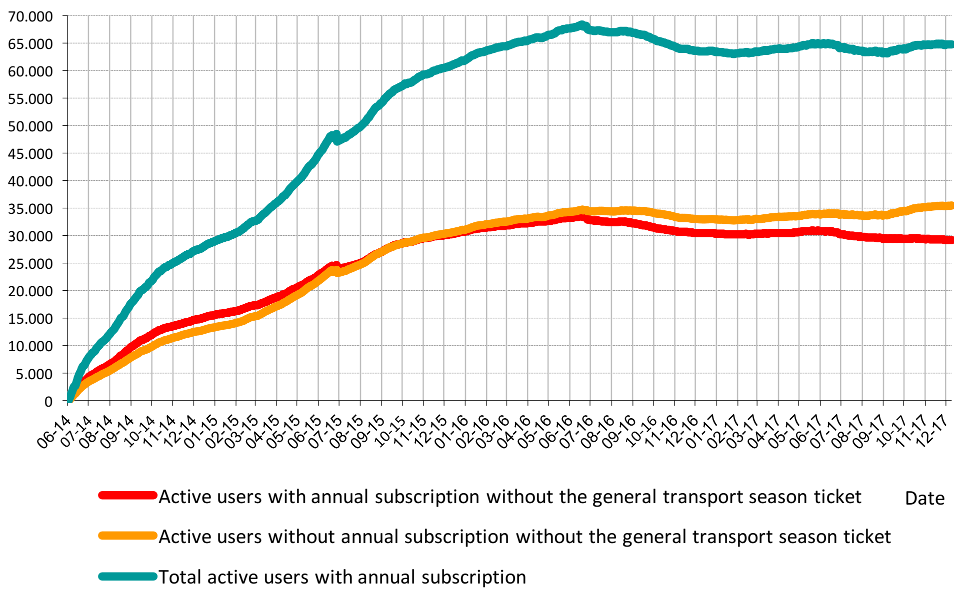
3.3.1 BiciMAD: birth and evolution

Part of the research conducted in this thesis is focused on the study of the cycling flow and the cycling accessibility derived from the Madrid Bike Share System, called BiciMAD. Therefore, it is convenient to provide an introduction to this system and the impact it has had on Madrid general cycling mobility patterns, in order to have the necessary framework to understand the research carried out and the results obtained.

BiciMAD was launched in June 2014, comprising 1,560 bikes and 123 docking stations and, after a first expansion phase in 2015, the system is currently operating with 2,028 bikes and 172 stations. A third expansion phase is meant to take place in 2018, adding 42 new stations and 468 bicycles to the system, — reaching 214 stations and 2,496 bicycles —, and the current plan is to comprise over 4,000 bicycles and 350 bike stations by 2019 (Lantiga, 2017). BiciMAD currently covers the inner-central area of Madrid, with nearly 850,000 inhabitants, and with approximately 8.9 million tourists in 2016 (Munkácsy & Monzón, 2017).

As the Figure 3.6 shows, in terms of number of users, BiciMAD experienced an important growth during the first two years, reaching the peak of 70,000 active users by June 2016, one year after the first expansion. This figure went slightly down for some months, but essentially the number of users has been stable over almost a year and a half now, with an average of 65,000 active users approximately. With the new expansion arriving in 2018, it is expected that BiciMAD experiments a new growth also in terms of users.

Figure 3.6: Evolution of active BiciMAD users (Madrid Open Data, 2017)



With respect to BiciMAD users profile, according to the Municipal Transport Enterprise (EMT) data (Lantiga, 2017), the age of the 80% of users ranges from 15 to 45 (it is important to remark that a minimum age of 14 years has been established), and two thirds of users are men. This imbalance in gender is significant, but also clearly lower than the imbalance found in the counts of casual cyclists already mentioned in the previous section. The EMT also highlights that, in terms of education, the 80% of users holds a university degree.

There are two types of BiciMAD users regarding the subscription to the system: frequent users and occasional users. Frequent users pay an annual membership (25€ in 2018) and then get lower renting prices that occasional users, who can obtain a free card for 1, 3 or 5 days and just pay for the trips done during these days.

Finally, BiciMAD users' cycling patterns will be analysed and discussed in the next section, focused on the visualisation and analysis of BiciMAD routes and cycling flow.

3.3.2 BiciMAD: characteristics and use or a fourth-generation system

BiciMAD is a modern Bike Share System. It employs a unique fleet of electric bikes, being one of the first fully pedelec-based systems worldwide (a convenient feature in a city like Madrid, with some hilly streets that might be an obstacle for cyclists), and it has built-in GPS trackers in all bicycles (originally implemented to avoid thefts, but useful in order to track cyclists' activity, as we will see in next section).

Actually, BiciMAD comprises almost all the characteristics and features of a fourth-generation scheme, such as: bicycle redistribution innovations (automated technologies, incentivising user-based redistribution, etc.), smart card integration with other transportation modes (public transport, car-sharing, etc.) or no smart card (identification by mobile apps), advanced pedalling technology, electric power-assisted bicycles (*e-bikes* or *pedelecs*, in theory with an electric pedal assistance up to 25 km per hour in the case of BiciMAD), bicycle tracking (GPS, RFID), state-of-the-art docking stations (solar power, touchscreen kiosks), online apps offering information such as real time availability of bikes at stations or flexible docking stations (in case of events) or no docking stations at all (mobile technology led smart lock) —the only feature of the previous mentioned that BiciMAD does not include— (Buehler & Pucher, 2012; Midgley, 2011; Munkácsy & Monzón, 2017; Shaheen, Guzman, & Zhang, 2010).

While registered users of most of bike-sharing systems do not pay for trips with a duration under 30 minutes, BiciMAD subscribers pay for any ride (€0.5 for trips under 30 min, and then according to a stablished fee), it principle in order to avoid trips by bike-sharing instead of walking, but also to partially refinance the expensive operation of implementing an electric power-assisted system. In any case, the €25 registration yearly fee for frequent users is relatively low compared to the one in other cities, such as London (€112), Budapest (€61), Barcelona (€47.16), Brussels (€32.6), Paris (€29 in 2014) (Munkácsy, 2017).

Another particular feature to be highlighted is that the redistribution of bicycles is partly user-based. In addition to the redistribution carried out by the system managers, the system stimulates users to return bikes to stations with a high proportion of free docks (with less than 30% occupancy) by providing a discount of €0.1 in the next trip.

3.4 Existing cycling infrastructure and current policies and future plans

3.4.1 Existing cycling infrastructure

Given the important social concern about cycling in terms of safety, revealed by the results obtained by recent studies in Madrid (CONECTA, 2015), the question about the role of cycling infrastructure arises. What is the existing infrastructure in Madrid and what has been the evolution of it, considering the relevant growth of the cycling mobility in the city?

Although over the last ten years, the implementation of cycling infrastructure has not followed the plans of the Madrid Cycling Master Plan launched in 2008, and has not reached the objectives in terms of cycling infrastructure, the city has experience an important progress.

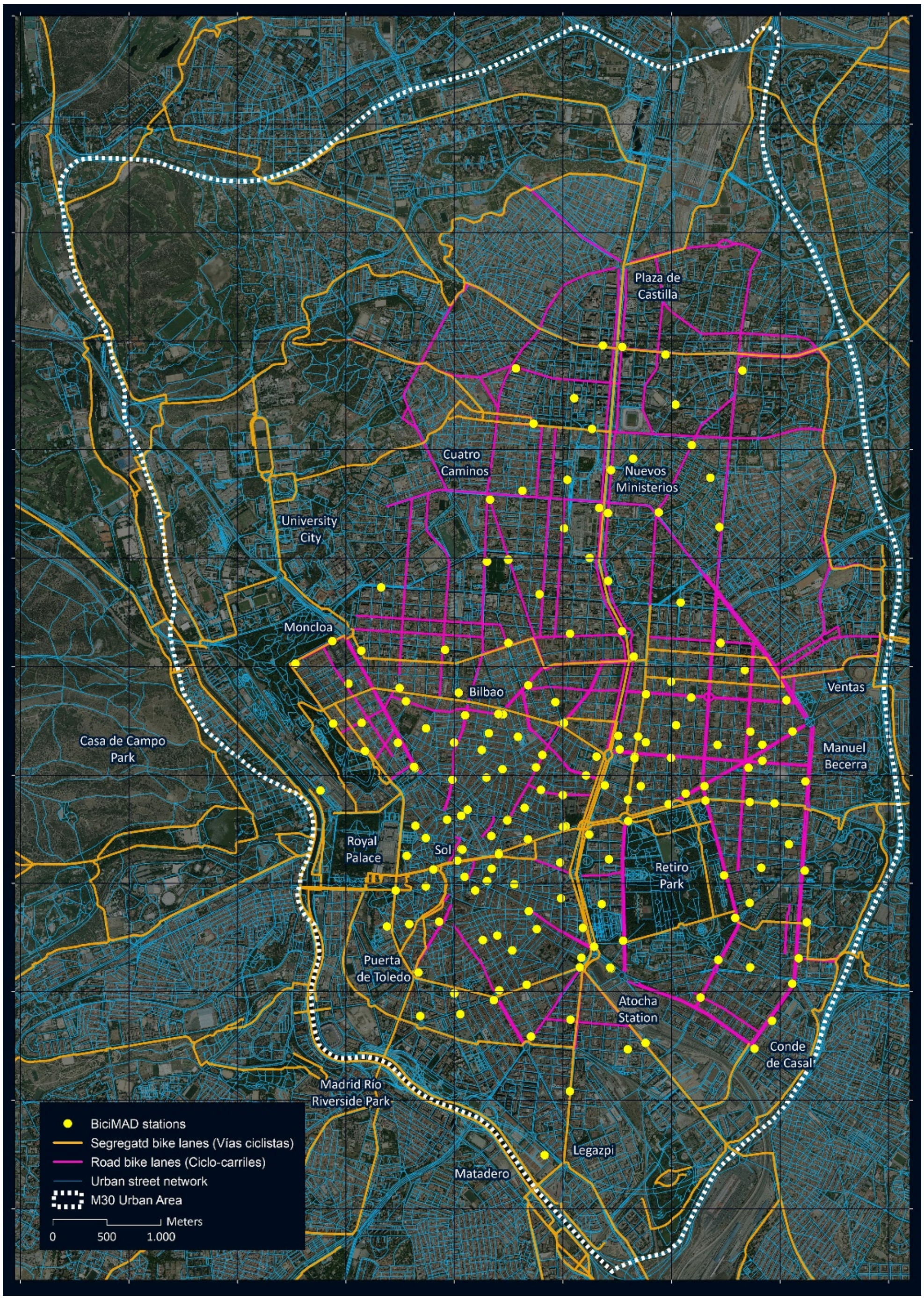
According to the documentation of Reviewed Madrid Cycling Master Plan (Kisters et al., 2016), in 2016 the total length of the cycling infrastructure, considering the different kinds of cycle lanes and paths, was 453 in 2016. This figure includes the 161 km network of *ciclo-carriles* implemented in 2014, when BiciMAD was launched. This new network basically does not correspond to physically segregated bike lanes, but mainly to road bicycle lanes (usually designated by a white stripe, a bicycle icon on the pavement and signage), coloured lanes (paint or other methods are used to colour bike lanes, making them more visible to motorists), traffic calming lanes, according to the mentioned study conducted by Pucher, Dill, & Handy (2010), cited when classifying the diverse types of infrastructure and plans recently implemented in cities worldwide. The 453 km also includes the 67 km that correspond to the cycling green-belt, a peri-urban infrastructure essentially used with leisure and sportive purposes.

In terms of bike parking infrastructure, Madrid has slightly improved the figures over the last years. While the number of bike parking racks was 1,242 and 1,269 in 2013 and 2014 respectively (Ayuntamiento de Madrid, 2015), today the city comprises 1,419 bike parking racks (Portal de datos abiertos del Ayto. de Madrid, 2018), and 45 additional resting areas with bike parking racks.

Other remarkable infrastructure recently implemented by the Madrid City Council is the network of 82 “*Avanza bicis”* in 2014 (Ayuntamiento de Madrid, 2015), infrastructure that correspond to the bike boxes (also known as advanced stop lines), according to the study conducted by Pucher, Dill, & Handy (2010), previously cited.

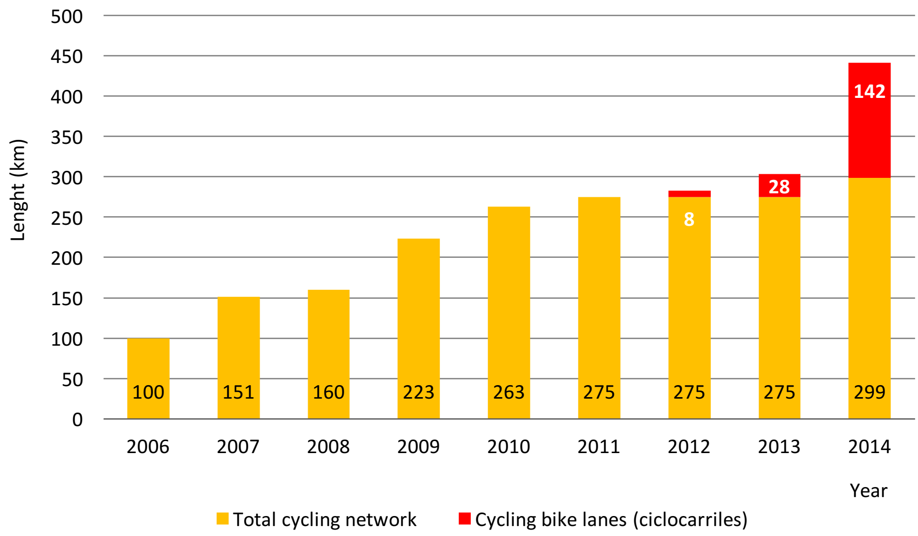
Figure 3.7 illustrates the two main type of bike infrastructure existing in Madrid, according to the Madrid City Council classification: “Ciclocarriles” (on road or non-segregated from traffic bike lanes) and “Vías Ciclistas” (bike lanes somehow segregated from traffic, not necessarily with a physical barrier). The data, updated in 2017, has been downloaded from the Madrid Data Council Open Data Platform (http://datos.madrid.es). A map representing this existing cycling infrastructure, along with BiciMAD bike stations, is provided in the annex.

Figure 3.7: Existing bike infrastructure.



The next figure (Figure 3.8) illustrates the evolution of cycling infrastructure in Madrid over the last years, according to the Report on the state of mobility in the city of Madrid (Ayuntamiento de Madrid, 2015), offering slightly diverse figures than the previously mentioned —and probably more accurate— considered by the Reviewed Madrid Cycling Master Plan (Kisters et al., 2016), but providing also a more general perspective (8 years) of the growth that the city experienced in terms of cycling infrastructure over the last years.

Figure 3.8: Total cycling network and cycling bikelanes



3.4.2 Current policies and measures and future plans

3.4.2.1 Current policies and measures

Although at a national level, the regulation framework on Mobility is outdated (it dates from 2003, since a draft from 2011 was never approved) and do not promote particularly policies to foster cycling mobility, diverse local plans have foster the user of bicycles in the city of Madrid. In addition to the specific plans implemented with this particular aim, such as the 2008 Madrid Cycling Master Plan (Ayuntamiento de Madrid, 2008) and the recent 2016 Reviewed Madrid Cycling Master Plan (Kisters et al., 2016), other plans promote cycling , such as The *Madrid city ordinance on Mobility* 2010, the Madrid Air Quality Plan 2011-2015, the Sustainable Mobility Plan of the City of Madrid (2014) or the Plan on Energy and Climate Change of the City of Madrid – Horizon 2020.

The *Madrid city ordinance on Mobility* 2010 (O*rdenanza de Movilidad para la Ciudad de Madrid* de 2010) allowed the city to implement some novel measures with that aim. For instance, it established that bicycles must keep on the center of the road lanes and makes mandatory to motor vehicles to respect them in that location, it provides a new legal framework for the implementation of road bicycle lanes (usually designated by a white stripe, a bicycle icon on the pavement and signage) and coloured lanes (paint or other methods are used to colour bike lanes, making them more visible to motorists), limiting motor traffic speed to 30 kph.

The Municipal Transport Enterprise (EMT) of Madrid has also recently implemented several measures with the aim of improving the integration of cycling within the global public transport network. In 2012, it became legal to introduce foldable bicycles in public buses and, in 2016, it improved the options to travel in the underground with bicycles at specific times (avoiding rush hours), and without limitations out of the M-40 peripheral highway.

3.4.2.2 Future plans

The most important local actions to take place in the immediate future with the aim of promoting cycling mobility in Madrid, are being channelled via the 2016 Reviewed Madrid Cycling Master Plan (Kisters et al., 2016), recently promoted by the Madrid City Council.

The plan aims at implementing 430 km of new cycling infrastructure in 8 years (2017-2025), executing an average of 50 km of cycling infrastructure per year. So, in addition to the approximately 140 existing km of cycling lanes, the objective is to reach a cycle lane network of 570 km by 2025. In order to achieve this goal, Madrid City Council plans to invest around 86 million of Euros during this period of time.

The planned network is denser in the centre, where there is a greater concentration of travel destinations and the highest levels of demand. The specific network defined by the plan can be consulted in the documentation of the 2016 Reviewed Madrid Cycling Master Plan (Kisters et al., 2016).

Figure 3.9: 2016 Reviewed Madrid Cycling Master Plan

Figure 3.10: Future cycling network by 2025, according to the 2016 Reviewed Madrid Cycling Master Plan

3.5 Conclusions

Madrid, as a case study, offers a number of relevant advantages when considering the research we aim at conducting. First, Madrid is undergoing a number of urban transformations which are changing different aspects of the city in a dramatic way. One of these aspects is mobility, and cycling mobility is specially emerging as bikes are at the center of recent urban policies and plans. Because of this, despite Madrid's relatively low "cycling culture", the city is more than valid as a case study since cycling mobility is growing significantly and there is a significant cycling activity to explore.

Second, this existing relatively low cycling activity in Madrid has led to the formation of an increasing number of cycling associations, which are working very actively with the aim of pushing local government to adopt new measures and develop new infrastructure oriented to promote cycling mobility. These associations have played an important role in this thesis with their support to the *Huella Ciclista de Madrid* participatory initiative, which will be introduced in the next section.

Third, although the existing cycling infrastructure may not be as wide spread as in other cities with a more relevant cycling culture, the city offers a rich variety of cycling infrastructure (different kinds of segregated and not-segregated bike lanes) which can be analyzed in terms of their real impact on cyclists mobility, as well as in terms of their role in the distribution of cycling flow across the city network (is cyclists flow essentially concentrated on streets equipped with cycling infrastructure?).

Fourth, Madrid offers, in addition, a wide variety of urban conditions that we want to explore: hilly streets as well as flat areas, quiet streets as well as roads with high motor-traffic intensity and even a changing weather which influence will be explored when analyzing some kinds of cycling mobility.

Finally, the recent and successful implementation of BiciMAD, allow us to include the analysis of bike share users, bringing the opportunity of comparing their mobility patterns to the one of casual cyclists and bike messengers, in the same city, under similar urban conditions.

4 Visualizing and analysing Madrid Bike Share System routes and cycling flow

Remarks

This section focuses on the visualisation and analysis of the cycling flow derived from the Madrid Bike Share System (BiciMAD) activity. It is based on the research synthesized in the paper titled *"The pulse of the cycling city: visualizing Madrid Bike Share System routes and cycling flow*" (Romanillos et al., 2018) published in Journal of Maps in Mars 2018.

Access to paper: https://www.tandfonline.com/doi/full/10.1080/17445647.2018.1438932

4.1 Introduction

With the aim of shifting towards a more sustainable urban transport model, cycling mobility is being promoted in many cities. This is done essentially by implementing different types of policies, by building cycling infrastructures and by fostering the implementation of Bike Share Systems (BSS). Although these bike share programmes have existed for over 50 years, they have gained popularity and have grown exponentially over the past 10 years, in general, worldwide (Fishman et al., 2013), and particularly, in Spain (Anaya & Castro, 2011). In consequence, recently-published research on BSS has been extensive, with different focuses. Some studies have visualized BSS activity, identifying trends usually based on the analysis of the docking stations' performance, observing the number of trips starting and ending at the station level (Borgnat et al., 2013; Zaltz Austwick et al., 2013a). Of great significance is the number of studies that analysed BSS imbalances produced by the different levels of attraction and generation of trips at the station level (Goodman & Cheshire, 2014), often with the aim of developing efficient bike redistribution strategies (J. H. Lin & Chou, 2012; Raviv et al., 2013). With the similar aim of implementing more balanced BSS, other studies have modelled demand (Systems & Lackner, 2013) or have developed models that optimize the location of BSS stations (García-Palomares et al., 2012).

However, as far as we know, the study of how BSS are impacting cities beyond the station level has yet to be addressed. While a significant number of studies have recently focused on the GPS analysis of casual cyclists' routes (Romanillos et al., 2016), based on tracks collected by apps such as Strava (Jestico, Nelson, & Winters, 2016), or based on the routes collected by research initiatives (Romanillos & Zaltz Austwick, 2015), only a couple of studies have focused on the exploration of real BSS routes. First, the route choice analysis performed by Khatri (2015), based on approximately 12,000 trips collected through the Phoenix BSS bikes equipped with built-in GPS trackers, and recently, the research published by Wergin and Buehler (2018), analysing 3,596 trips obtained by introducing GPS trackers into 94 bikes in the Washington DC BSS in 2015. Given the exponential growth of BSS in many cities across the world, the study of the real BSS users' routes must be addressed in further depth. How is the BSS cycling flow distributed across cities' street networks? What are the paths that the BSS users follow? What are the most important arteries of the city in terms of cycling flow? These are important questions to answer in order to understand the current use of BSS across the city and, in consequence, in order to obtain the necessary understanding to promote efficient policies and infrastructure where they are really needed.

The goal of this study is to visualize the Madrid BSS (BiciMAD) cycling flow, obtained from processing over 250,000 GPS routes, and to provide an analysis of how this flow is distributed across the city street network at different moments (studying the different levels of use over the course of the day, or during the weekdays, weekends or holidays). It also explores the cycling patterns that correspond to different types of BSS users (frequent users vs. temporal users or tourists). The visualization of these different levels of BiciMAD cycling flow is presented here through the Main Map and through a video-visualization that illustrates the BSS cycling flow over the course or a day.

4.2 Case study, data and methodology

4.2.1 Case study and data

This research focuses on the study of the cycling routes and flow derived from BiciMAD, the Madrid Bike Share System, which has already been introduced in Section 3.

The study considers the two main types of bike infrastructure in Madrid, according to the Madrid City Council classification: "*Ciclocarriles*" (on-road or non-segregated from traffic bike lanes) and "*Vías Ciclistas*" (bike lanes somehow segregated from traffic, not necessarily with a physical barrier). The data, updated in 2017, was downloaded from the Madrid Data Council Open Data Platform (http://datos.madrid.es). Figure 3.7 represents this existing cycling infrastructure, along with BiciMAD bike stations.

The study is based on the analysis of a collection of data provided by the Municipal Transport Company (EMT), which is currently managing BiciMAD. The dataset corresponds to the 253,556 routes recorded by the BSS during April 2017, although we left aside the trips derived from BSS redistribution and focused on the analysis of the resulting 230,238 trips. For each trip, the dataset provided information on both origin and destination stations and docks, the duration of the journey in seconds, the specific date and starting time (aggregated per hour, in order to protect the anonymity of users), age according to 6 ranges (0-16, 17-18, 19-26, 27-40, 41-65 and over 65), and the type of user (frequent user, occasional user, and unknown user, with 215,371, 4,578 and 10,289 routes for each group, respectively). Based on the date field, we classified the routes according to four different typical days, considering that they could present different travel patterns. More specifically, we identified and categorised the trips that took place on the weekdays from Monday to Thursday, on Fridays, at the weekends and on holidays (considering Easter, from Thursday 13 to Sunday 16 April 2017). Unfortunately, users' ID were not provided, for data protection policy reasons, so that interpersonal variations among cyclists could not be analyzed.

The dataset provided by the Municipal Transport Company (EMT) was basically a collection of GPS track points, recorded with an average interval of 75 seconds. This temporal resolution is much lower than the one typically obtained with commercial smartphone apps or GPS devices (Romanillos and Zaltz Austwick 2015), which tends to be around 2 seconds. In consequence, the real map-matched route lines had to be estimated as the shortest path between the track points, as we will explain later. The track lines were map-matched to a detailed street network, based on the March 2013 version of

TomTom® for the Spanish road network, which is currently the most accurate street network we have found in Madrid. It consists of over 160,000 street segments for the metropolitan area of Madrid that covers the collected BSS cycling routes, and includes not only roads, but also pedestrian streets and basic bike infrastructure. For greater accuracy, we edited the network and updated the bike infrastructure, including all the eight different kinds of bike infrastructures included in the Madrid Cycling Master Plan.

In addition, the main maps include the most updated orthophoto (2016) from the Spanish Geographic Institute Aerial Photographic Plan (PNOA), as a faded background base map.

4.2.2 Methodology

First, the JSON track points were imported as GeoJSON files into a GIS environment using Python programming language and the free and open software Mongo DB. Then, we exported the GeoJSON track points as Geodatabase point feature classes using the free and open software QGIS, and subsequently generated the GPS track lines by joining the track points. We eventually map-matched the GPS track lines to the detailed street network previously described, obtaining what we call the map-matched route lines, by estimating the shortest path between the track points, according to Dijkstra's algorithm, using the New route ArcGIS's Network Analyst tool (vs. ArcMap 10.4).

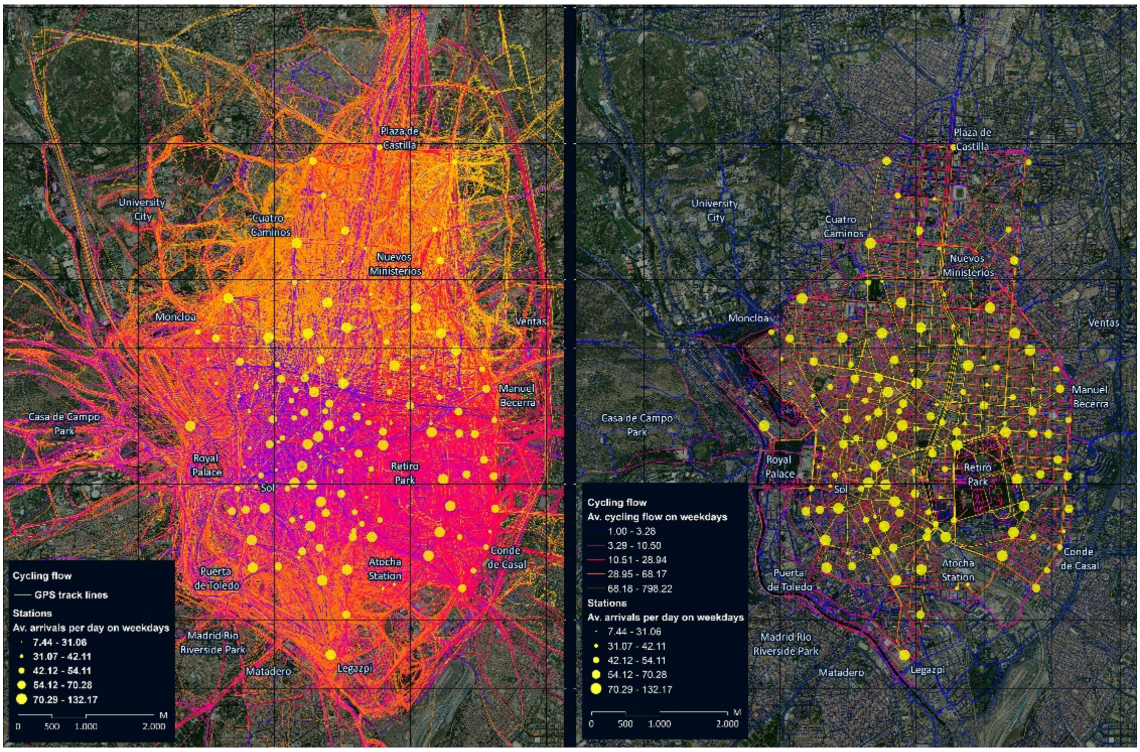
Then, these estimated real routes, or map-matched route lines, allowed us to calculate the real trip distance and, by considering the duration of the journey, to calculate the average trip speed. Since we had information on the type of user and the date and time of every journey, we decided to analyse the average trip distance, duration and speed according to different periods of time and types of users. The general results are shown in Table 4.1, Figure 4.3 illustrates the number of trips according to distance and user type, and we discuss the results in the next section.

Our main goal was to generate diverse maps showing the cycling flow derived from BiciMAD, assigned to the street network. In order to do so, we split the map-matched routes according to the street network junctions, and we then summarized the number of trips at the street-segment level, for the two different scenarios, illustrated on the Main Map. The first scenario corresponds to the average cycling flow on a weekday, and the second scenario to the average cycling flow on a weekend day. In order to better understand the cycling flow dynamics, we also decided to calculate and represent the activity at the BSS station level, adding up the number of departures and arrivals at each station, so we can easily relate the most important streets in terms of cycling flow to the most significant stations in terms of attraction and generation of trips, for the two scenarios considered. Figure 1 illustrates the BSS cycling footprint by representing the original GPS track lines, as well as by visualizing the street-network assigned flow derived from the map-matched route lines.

In addition to the maps that illustrate the different BSS dynamics during weekdays and weekends, we analysed the use of the BSS over the course of a day, based a graph that illustrates the percentage of trips per hour (Figure 5), and based on some statistics regarding cyclists' average speed and trip distances, according to the following 7 time intervals (7-10h, 10-13h, 13-16h, 16-19h, 19-22h, 22-1h and 1-7h). We defined these time intervals in order to distinguish the different travel patterns that corresponds to the diverse peaks of activity identified in the Figure 5.

This analysis of BiciMAD activity over the course of a day was performed for each of the four different typical days defined previously (Data sub-section), in order to identify potential differences. Figure 4 illustrates the aggregated number of trips for each type of day and time interval. Finally, the video-visualization illustrates BiciMAD routes over the course of a day by merging all the routes from a single week (from the 17th to the 23rd of April), making the difference between the weekday and the weekend routes.

Figure 4.2: GPS track lines (left) and assigned cycling flow considering map-matched routes (right)



4.3 Results

4.3.1 Results on BiciMAD cyclists' travel patterns

The results obtained clearly illustrate the different dynamics of use that BiciMAD experiences over time and according to its different types of users. First, the analysis of average trip distances, durations and speeds, reveals significant differences, as is shown in Table 4.1. The most remarkable observation are the radically different figures shown by frequent and occasional users. While the average frequent users' cycling speed is 14.29 kph occasional users' is only 8.59 kph. Although frequent users have more experience and, in consequence, may be more confident and able to circulate at a higher speed, considering that most of these occasional users are tourists, the most probable reason for such a dramatic difference is the fact that tourists tend to stop at different points and take their time to observe and enjoy the city. The average speed is for a tour visit, which is the main purpose of the journey, not just travelling from one location to another. The difference shown in terms of trip distance is most likely due to the same reason: the average distance travelled by frequent users is 3.01 km, while occasional users' average distances almost double this distance, rising up to 5.52 km. When it comes to the average time, the average trip duration is three times that of occasional users, with 15.9 and 48.5 minutes, respectively. Occasional users' figures are quite different from frequent users, not only during weekdays, but also with regard to weekends and holidays, when the purpose of the journey will most likely be related to leisure activities, not commuting. During weekends and holidays, frequent users' trips are slightly longer than during the weekdays, and the average speed is somewhat lower than during the weekdays (3,256 m vs. 2,933 m and 13.44 kph. vs. 14.35 kph. respectively).

Table 4.1: Basic route statistics according to different periods of time and type of users

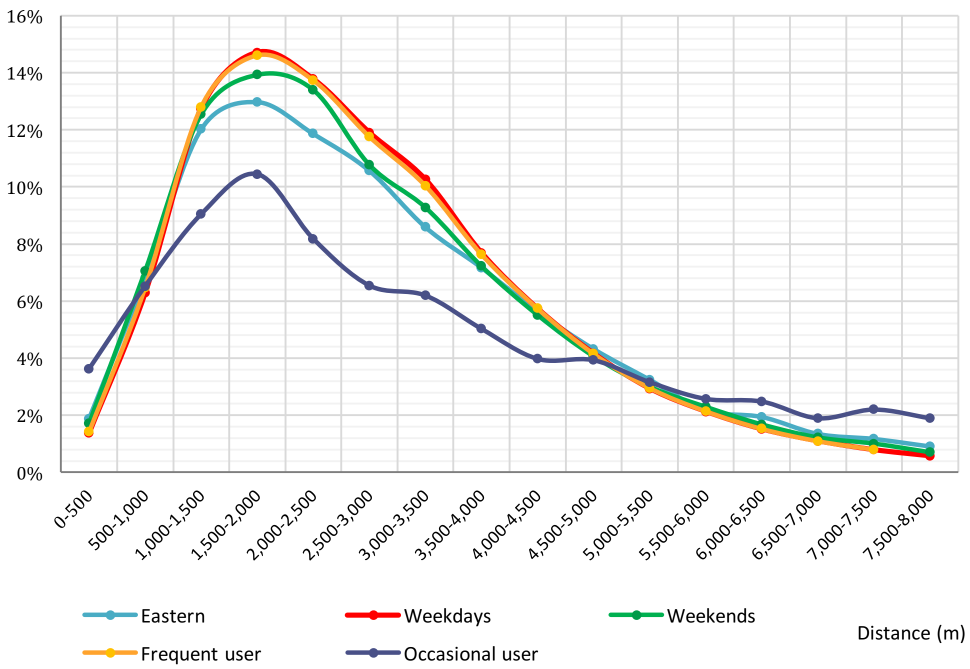
Target routes	Av. Speed (kph)	Distance (m)	Av. Time (sec)	Av. Time (min)	Count
Total routes	14.06	3,104	1,028	17.13	226,253
Type user 1 (Frequent user)	14.29	3,011	954	15.90	212,012
Type user 2 (Occasional user)	8.59	5,518	2,910	48.49	4,279
Weekday routes	14.35	2,993	948	15.79	158,246
Weekend routes	13.44	3,256	1,161	19.34	49,700
Eastern routes	13.24	3,652	1,363	22.71	18,307
Weekday Frequent users	14.51	2,935	898	14.96	150,246
Eastern Occasional users	8.81	5,940	2,943	49.05	1,773
Weekends occasional users	8.55	5,641	2,998	49.97	1,056
Weekends frequent users	13.76	3,120	1,054	17.57	45,232
Basic route statistics of frequent users during weekdays over the course of the day					
7-10h	15.71	2,962	829	13.82	28,002
10-13h	13.20	3,280	1,206	20.09	25,354
13-16h	13.78	3,167	1,075	17.92	41,246
16-19h	13.70	3,305	1,134	18.89	46,341
19-22h	13.50	3,049	1,026	17.10	47,694
22-01h	14.62	2,833	874	14.56	27,124
01-07h	15.53	2,874	884	14.74	10,492

Another remarkable difference is found when analysing frequent users' figures over the course of the day. The average speed of frequent users' trips during the morning peak hour is the highest, at 15.71 kph, which can be associated to the rush typical of commuting trips. The average speeds during the rest of the day are clearly lower, around 13.50 kph, before they once again rise after 10pm, and especially after 1am. Our hypothesis regarding this fact, is that this increased speed at night could be explained by the quasi-absence of motor traffic, which means that cyclists most likely do not stop at every junction or traffic light, significantly reducing travel time.

A deeper understanding of cyclists' travel distances is provided by Figure 4.3, which illustrates the percentage of routes according to distance intervals in a different line graph for trips during weekdays, weekends and holidays (Eastern), and also for frequent and occasional users. Although the average distances are different (especially between frequent vs. occasional users), we observe a similar pattern for all of them, with the highest percentage of trips always close to a 2 km. distance. The distribution is asymetric, with a low percentage of trips under 1km distance (less than a 8% of the total trips), a distance that could by reached by walking in approximatelly less than 15 minutes, considering an average walking speed of 4 kph, something quite reasonalbe accoding to different studies (Bohannon, 1997; Fritz & Lusardi, 2009). In addition, we have to consider that the shorter the trips, the more important becomes, in relative terms, the distance people have to walk from their origins to the starting bike and from the destination bike stations to the final destinations. In the next section we could study this phenomena when comparing these graphs to the one obtained from casual cyclists, who do not have to add these extra distance and, in consequence, may be willing to do shorter trips cycling.

The analysis of BicMAD routes according to average time revealed that 92.6% of frequent users' trips are under 30 min length, so the €0.5 fee for trips under this duration is applicable to the vast majority of the trips. Considering frequent users' average speed, a 30-minute trip is 5,436 m in distance. Figure 4.3 also clearly illustrates the low percentage of trips above this distance.

Figure 4.3: Percentage of trips according to distance



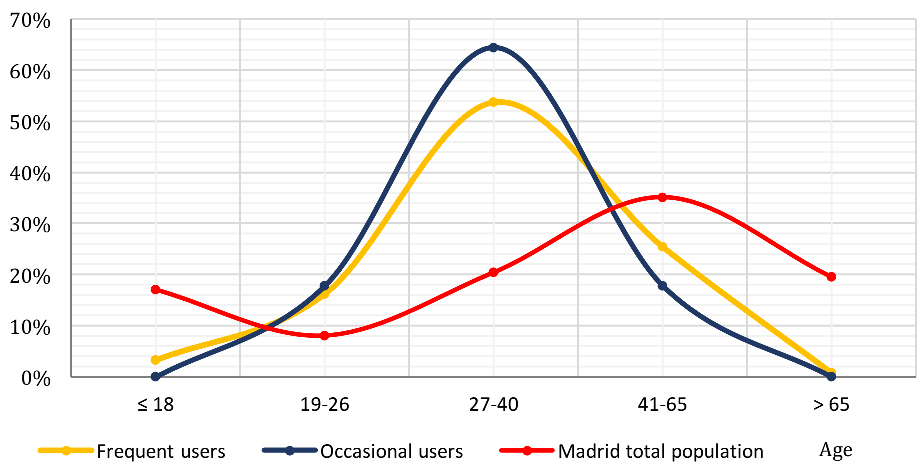
The analysis of trips according to distance is complemented with the analysis of accumulated trips according to distance, revealing important facts. Figure 4.4 represents the percentage of accumulated trips according to distance.

Although according to Figure 4.3, the trips with an average distance approximately 2,000 m are the most common, the 65% of trips cover a greater distance, in all the cases with the exception of occasional users, in which case the percentage of trips over 2,000 m is even greater (70%).

When analysing trips according to distance, it is important to consider that the length of BSS users' trips is determined by the extension of the are covered by such BSS. In the case of Madrid, although BiciMAD has already experimented a first expansion phase, the system only covers the centre of the city. It would be important to analyse the consequences of future expansions in terms of trip distance, as well as to compare these average distances to the one of casual cyclists, who do not have this restriction. This question will be address in the next section.

The analysis of BiciMAD users' travel patterns according to age reveals some interesting findings. Figure 4.5 represents the percentage of users according to 5 age ranges (0-18, 19-26, 27-40, 41-65 and over 65), after merging the first two age-range groups originally provided (0-16 and 17-18), and

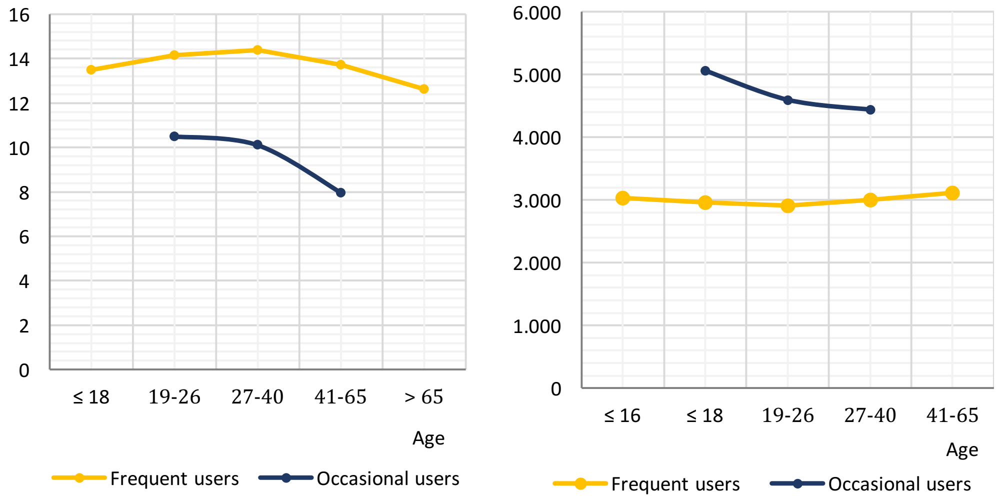
Figure 4.5: Percentage of BiciMAD users according to age



considering both frequent and occasional user groups (based on a sample of 212,012 and 4,279 users, respectively). Figure 4.5 reveals an important concentration of users between 27-40 years old, especially when comparing the percentages with Madrid's total population (Madrid City Council, 2017). Users between 27 and 40 years old are approximately 50% of users, in the case of frequent users, and significantly more in the case of occasional users, at almost 65%. Occasional users do not necessarily provide age information through their registration process, and in this case, our original sample is reduced to just 73 users, corresponding to a 9.5% statistical sampling error with a statistical confidence level of 90%. This low sample may explain the complete absence of occasional users in the first and the last age-range groups. In any case, their representation is certainly low in the case of frequent users, with just 0.80% and 0.73% for the (0-18) and the (>65) age groups respectively.

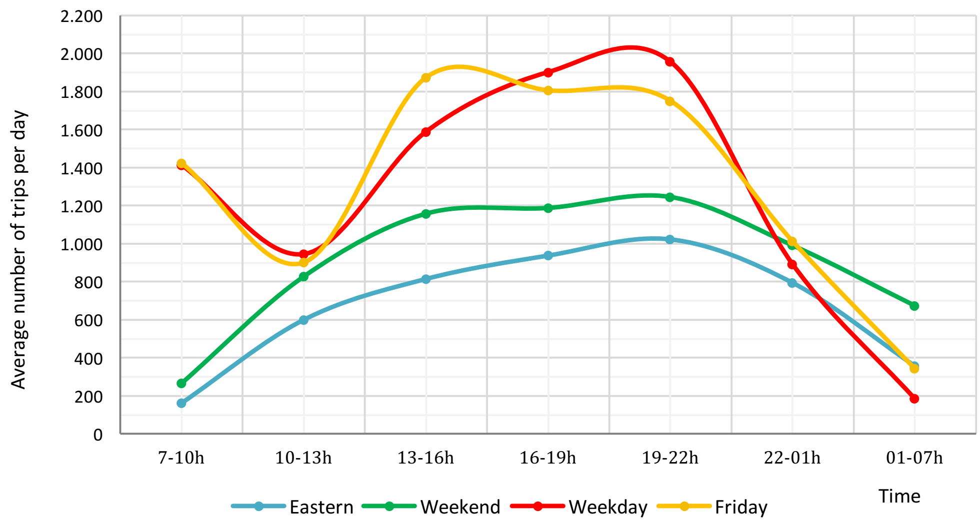
Analysis of average cyclist speed and trip distance according to age reveals certain patterns. As Figure 4.6 illustrates, in the case of Frequent users, average cycling speeds and average trip distances remain quite stable, with slighly higher speeds and shorter trips in the age group between 27 and 40 years old. Age seems to affect more occasional users in both speed and distance, with a drop in values as the age is increased. The absence of occasional users in the first and the last age-range groups makes these graphs uncomplete.

Figure 4.6.a: Average cyclists' speed (kph) and Figure 4.6.b: Average trip distance (m)



With regard to the evolution of BiciMAD activity over the course of a day, we can based our analysis on the Figure 4.7, which represent this activity by aggregating the number of trips according to 7 time intervals and classifying the trips that took place on the weekdays from Monday through Thursday, on Fridays, on the weekends and on holidays (considering Eastern, from Thursday 13th to Sunday 16th of April).

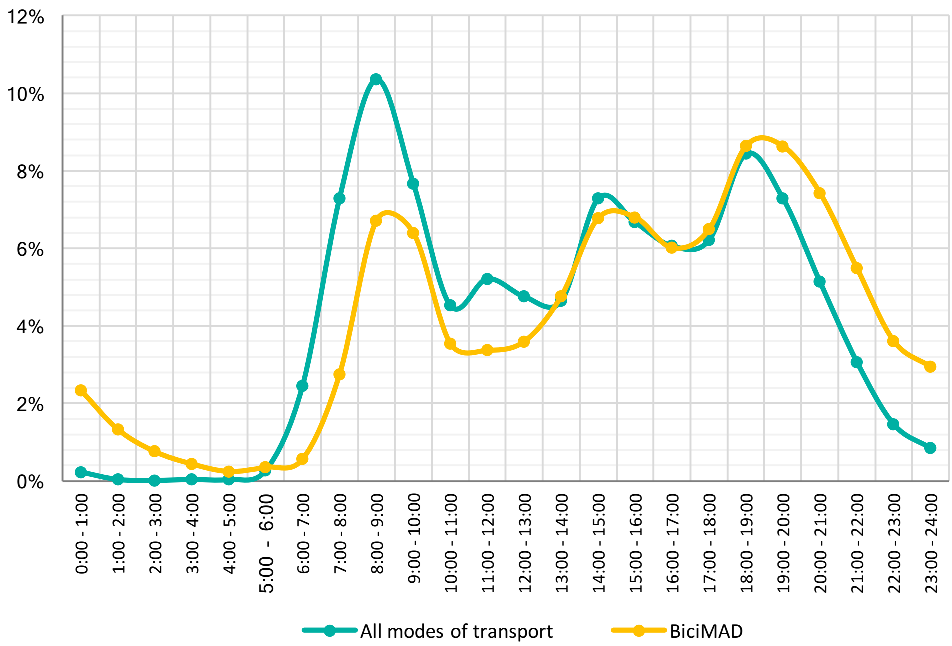
Figure 4.7: Average number of trips over the course of a day



The figure shows a very different pattern when comparing weekday activity vs. weekend and holiday activity. Weekdays shows a clear morning peak hour that corresponds to commuting trips, and then a second peak in the afternoon and evening, which is earlier in the afternoon on Fridays. This is due to the fact that it is common to finish working early on Fridays in many companies or sectors. The morning peak will most likely also be associated with the use of BSS for first and last-mile public transit connections, explaining the important activity of some stations close to transport hubs (such as Atocha or Moncloa), illustrated by the Main Map. Weekends and Eastern days' activity perform in a similar way, with a reduced activity early in the morning and a continuous increase towards the afternoon and the evening. The night activity during in these cases after 1 AM is also remarkable, showing an important use of BiciMAD associated with nightlife during weekends and holidays, which is characteristic of the city of Madrid.

To what extent BiciMAD activity correspond to the general travel patterns of Madrid? In order to respond this question, we have compared the number of BiciMAD trips per hour to the number of total trips per hour that correspond to all transport modes according to the last Mobility Survey conducted in Madrid (Consorcio Regional de Tranpsortes de la Comunidad de Madrid, 2014). In order to compare the data, we just consider here BiciMAD weekday trips, since the Mobility Survey correspond to the mobility of a working day in Madrid Region. Figure 4.8 illustrates this comparison, showing an important similarity and some differences as well. Essentially, BiciMAD presents the same remarkable three peaks of activity but, in the case of BiciMAD, the most important peak of activity during weekdays is the one of the evening (8.5% of trips, approximately) while the most important peak of activity is the morning one when considering all transport modes (10.5% of trips, approximately).

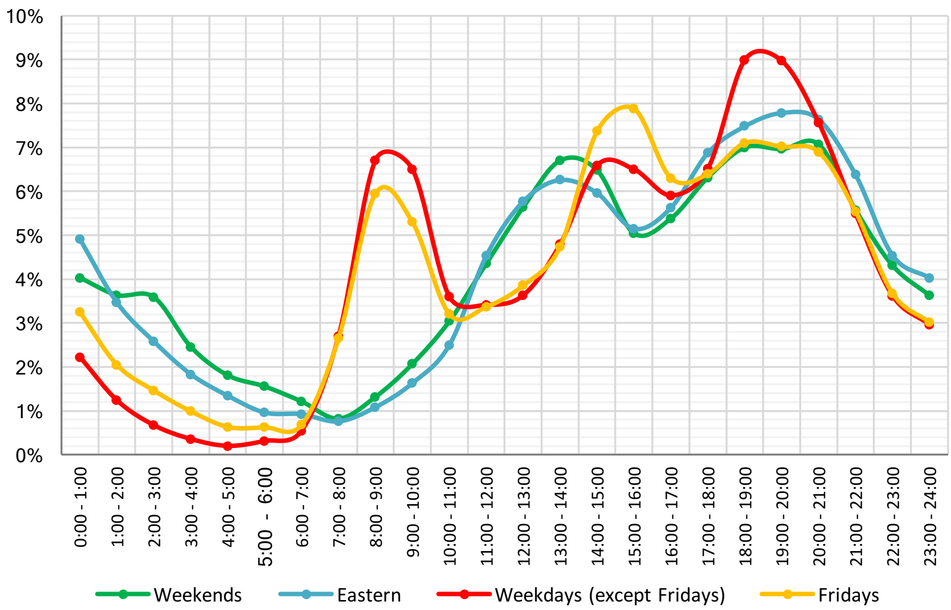
Figure 4.8: Number of trips per hour over the course of a weekday (%)



Another difference is the slight time gap that the graph shows when comparing morning and evening peaks. BiciMAD morning peak takes place from 8h to 10,30h, while the morning peak considering all transport modes starts earlier (around 6h), finishing at the same time approximately. More clear is this gap in the case of the evening peak, with a similar peak between 18h to 20h, and then showing a gap of approximately one hour when from since then. This gap does not exist in the case of the afternoon peak, where the graphs match almost perfectly both in time and percentage of trips.

When extending the representation of the number of trips per hour in BiciMAD, considering not only weekdays, the different peaks of activity are better identified as well. As Figure 4.9 shows, the graphs representing Fridays' activity and the rest of the weekdays' activity are similar, with the exception of the flip between the afternoon and the evening peaks that was previously highlighted. The graphs representing Weekend and Eastern activity are also similar, but in this case the three peaks can be better identified than in the previous Figure. Instead of showing a morning, afternoon and evening peak, the graphs show clear afternoon, evening and a night peak that reaches the maximum share around 1h, and maintain an important activity until 3h in the case of weekends activity, when, despite the vivid nightlife of Madrid, other transport modes have already finished its service (at 1:30h in the case of the tube) or reduce it (in the case of many bus lines.

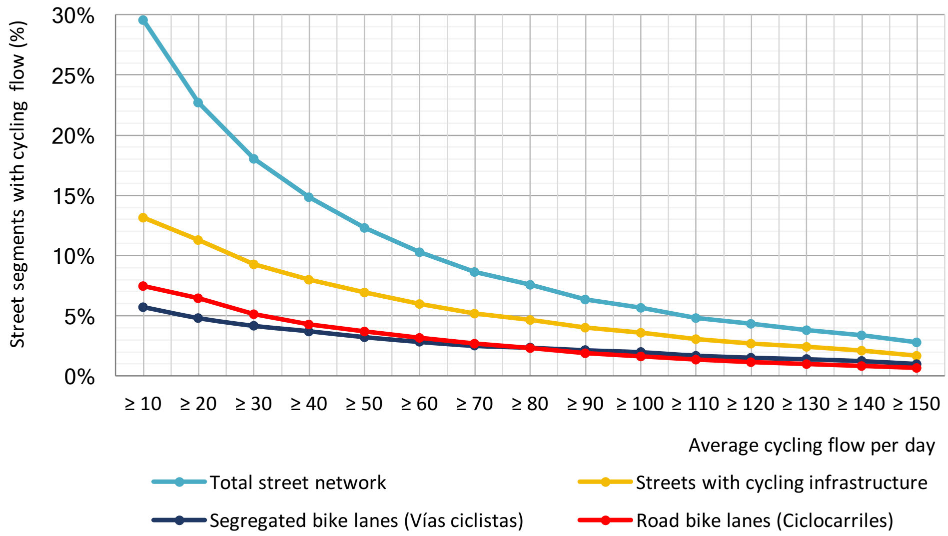
Figure 4.9: Number of trips per hour over the course of a day (%)



4.3.2 Results on BiciMAD cycling flow distribution across the urban network

Although the main map visualises distribution of the cycling flow from BiciMAD activity across the street network, as we explain in the next section, we considered it necessary to analyse this distribution in further detail. With the aim of understanding the extent to which cycling flow is more or less distributed across the urban street network, we calculated the percentage of street network segments that supported different amounts of cycling flow, as Figure 4.10 illustrates.

Figure 4.10: Street network segments with cycling flow (%)



This figure reveals, for instance, that all the street segments with an average cycling flow per day over 10 (in other words, the streets with an average of over 10 BiciMAD users who ride along them per day), is concentrated in 30% of the urban street network, while only approximately 5% of the street network segments have an average cycling flow over 100. This graph reveals how concentrated cycling flow is in Madrid, but we find the possibility of comparing this graph to the graph of other case studies interesting, since cities with high cycling flow concentrated in a few streets could be easily distinguished from the cities where cycling flow is more distributed. It is important to highlight that, when analysing this distribution of cycling flow, we are only considering the street network within the M30 peripheral street of Madrid, which is the boundary of the area currently covered by BiciMAD. This area is illustrated in Figure 8, which at the same time represents the existing cycling infrastructure.

In addition, with the aim of discovering the amount of cycling flow captured by the existing network of cycling infrastructure, we have repeated these calculations, considering independently the streets with segregated bike lanes (*Vías ciclistas*) and the ones where road bike lanes —non-segregated from traffic— (*Ciclocariles*) have been implemented. Figure 4.10 illustrates, for instance, that approximately 14% of the streets with an average cycling flow per day over 10, is concentrated in streets with any kind of cycling infrastructure, and that the percentage of network segments that correspond to streets with road bike lanes or segregated bike lanes is approximately 8% and 6%, respectively. These results provide highly valuable information for planning new bike lanes in Madrid.

If we analyse in detail Figure 4.10, we can see that while the percentage of road bike lanes (Ciclocarriles) is higher than the one of segregated bike lanes (Vías ciclistas) for street network segments with low cycling flow, this is not the case when considering street networks with an average cycling flow per day over 80. In order to provide a deeper insight into this flipping trend, we produced a graph (Figure 4.11) illustrating the percentage of cycling flow along streets with cycling infrastrucuture, again making the distinction between streets with segregated bike lanes (*Vías ciclistas*) and the ones where road bike lanes —non-segregated from traffic— (*Ciclocarriles*).

Figure 4.11: Cycling flow along streets with cycling infrastructure (%)

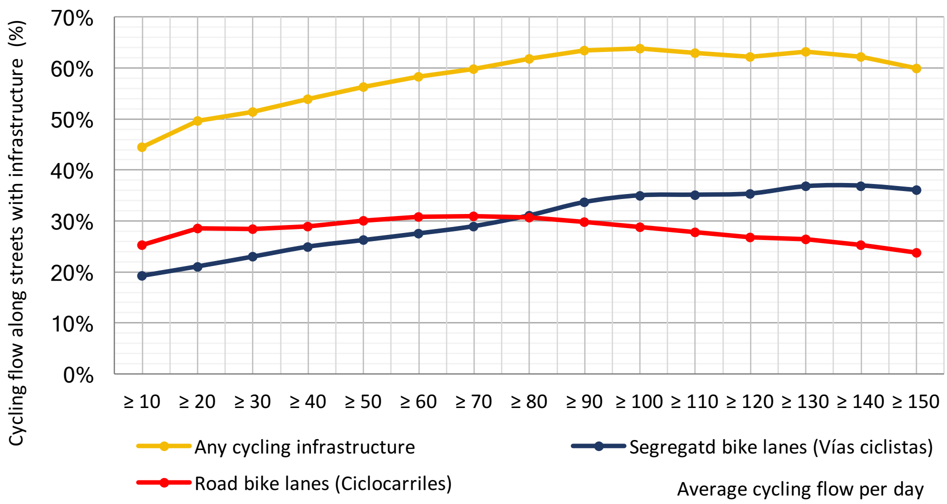


Figure 4.11 clearly illustrates that the cycling flow “captured” or “supported” by road bike lanes (*Cicloccarriles*) remains stable or even decreases slightly in the case of the streets with the highest cycling flow (over 80), while segregated bike lanes (*Vías ciclistas*) show an stable increase, supporting almost the 40% of the cyclists routes with the highest cycling flow (over 150 cyclists per day).

Finally, it is important to measure or quantify this the cycling flow “captured” or “supported” by streets with cycling infrastructure in relation to the number of street-network segments with such infrastructure or in relation to the length these network segments. Table 4.2 shows this information. Now, we can state that approximately the 35% of streets with a cycling flow over 150 cyclists per day correspond to streets where segregated bike lanes have been implemented, considering the fact that only a 17.48% of the street network segments correspond to this cycling infrastructure. It also possible to compare the “attractiveness” of this infrastructure to the one of road bike lanes (Ciclocarriles), which support approximately the 22% of the street segments with the same level of cycling flow (a 33% less that the segregated bike lanes), with the 11.74% of the street network segments corresponding to this cycling infrastructure (also around a 33% less that the segregated bike lanes). In this case, we could conclude that both infrastructure have a similar impact in streets with the maximum level of cycling flow.

Table 4.2: Length and number of segments of the street network within the M30 in Madrid

Network	Total network length	Network length (%)	Total number of segments	Number of segments (%)
Total street network	1,422,243	100.00%	32,360	100.00%
With cycling infrastructure	328,010	23.06%	8,653	26.74%
With segregated bike lines	191,609	13.47%	5,658	17.48%
With road bike lines	136,401	9.59%	3,798	11.74%

4.4 The Map

The Main Map (attached at the end of this section) illustrates the cycling flow derived from the activity of Madrid BSS, assigned to the street network, after the process of map-matching thousands of GPS tracks collected by the system. The canvas includes two maps that illustrate the cycling flow in two different scenarios with a different focus.

The map on the left visualises the average cycling flow on a working day. The street segments are represented according to the average cycling flow, assigned by summarizing the number of total trips while overlapping each street segment over the month's working days and divided by the amount of working days in April (18). Regarding symbology, the flow ranges correspond to a quantile distribution. The map provides us with an overall view of the cycling footprint and its extension across the city network, and allows us to identify the most important arteries in terms of cycling flow, such as the two most important north-south axes (Bravo Murillo street and the Paseo de la Castellana Avenue), and other important east-west axes (Calle Mayor or Alberto Aguilera). Representation of activity at the BSS station level, by aggregating the number of departures and arrivals at each station, provides a better understanding of BSS flow, since the most important cycling streets clearly connect the most relevant stations. The departures and arrivals are represented according to proportional circles, whose ranges and sizes also fall under a quantile distribution. The yellow-filled circles represent the average number of arrivals per day and the white circles the average number of departures per day. The overlapping circles provide information about the balance or imbalance of the stations in terms of attraction and generation of trips.

The map on the right focuses on the cycling flow on a weekend day, by representing, for each street segment, the difference between the average cycling flow on a weekend day and the cycling flow on a weekday, rather than by solely representing the cycling flow on weekends. By doing so, the difference between both scenarios becomes much clearer. In this case, yellow lines represent positive values; in other words, street segments where there is a greater cycling flow over the weekends than on weekdays. The rest of the colours represent negative values (streets with less activity during weekends) with ranges defined according to a quantile distribution. The overall footprint reveals significant differences, such as the increase in cycling flow in the most important parks of the city, including Madrid Río, the riverside park, the Casa de Campo, and some areas of El Retiro. However, this latter park also shows important activity on weekdays, since it is a more central and urban park. Other areas show a radical decrease in activity (the ones in dark blue), such as the Paseo de la Castellana and Bravo Murillo north-south axes, among the most important during weekdays. The activity shown at the station level also presents remarkable differences, with a strong concentration of activity in the stations around the city centre, and less activity around the Paseo de la Castellana, which is more connected to the financial and business centres of the city.

Both maps are quite complementary and illustrate the different uses of the city street-network over time well, in terms of cycling flow, and this may constitute a valuable tool when defining the increasingly-common different cycling policies and measures that many cities are adopting temporally for weekdays and weekends. Although it may seem obvious, it is important to highlight that both footprints are somehow determined by the extension of the area covered by the BSS stations. The absence of bike stations in the University City or in the Casa de Campo Park, for instance, explains the low cycling flow values obtained in these two areas.

4.5 Dynamic visualization

A video-visualization was produced with the aim of representing cyclist flow in a dynamic way, which could provide an idea how the immense volume of trips generated by BiciMAD evolve over time. The visualisation was produced using the *Processing* programming language (http://processing.org), using code written for this purpose (https://github.com/martinaustwick/GPS-from-MySql/tree/GPS-from-geojson). The journeys were exported as geojson files, and a processing sketch was converted from geojson to .csv, which is more quickly read by Java/Processing (resulting in a 10s for csv vs. a 120s import time for geojson, for files of similar size, on a 2017 *MacBook Pro*). The 63,000 journeys were imported into memory in *Processing*.

Figure 4.12: Video visualization screenshot (Link to web).

Processing calculates the total length of the route and uses the durational information to create an average speed, and waypoints - locations where a bike is at a specific time point. An internal clocks updates, and the code displays all data points the bike has visited since the last frame. In between frames, a partially transparent version of the underlying map is redrawn, meaning that the location of points in previous timestamps remains partially visible, creating the illusion of a continuous path. By decreasing transparency (increasing alpha value), those previous values become more strongly obscured, emphasising the "current" position of cyclists; by increasing transparency (reducing alpha), prior paths are more obvious, at the expense of the most current data. With each frame, a .jpg image is captured, creating some 6,480 images (8 hours at 6 images per minute) which, when assembled at 30 frames/second, results in a movie of under four minutes. Finally, the video was edited with *Adobe Premiere CS6*.

4.6 Conclusions

Estimation and visualisation of the cycling flow derived from Bike Share Systems across the street networks is crucial in order to have an overall understanding of the current use of BSS across the city, beyond the station level, and, in consequence, in order to promote efficient policies and infrastructure for the improvement of cycling mobility. This research answers the questions raised in the introduction section: how is BSS cycling flow distributed across the street network of cities? What are the paths that the BSS users follow? What are the most important arteries of the city in terms of cycling flow? Doing so in a visual way provides an important tool for policy makers, as well as for BSS managers.

This study also evidences the importance of analysing and representing the evolution of BSS dynamics over time. Illustrating different BSS activity on weekdays and on weekends or holidays provides relevant information to consider when promoting policies or measures for specific periods of time, something that has become a trend in many cities. For instance, closing certain streets to motor traffic, in order to promote pedestrian or cycling mobility during weekends, Sundays, or specific holidays. In addition, analysing the use of the BSS over the course of the day and according to the different types of users provides important information in terms of the use of the system and the distribution of cycling flow during potential peak hours; for instance, this is crucial for the adoption of specific measures for these intervals of time at specific locations. At the same time, it identifies age profiles to be addressed as future target users of BiciMAD.

It is also clear that further analysis on the same data could enhance Madrid cycling network design and management. For example, the study almost directly yields most frequented O-D relationships non-covered with cycling infrastructure; or, it could be used to assess different options on specific itineraries, according to existing cyclist traffic levels

Future work should focus on continuing to monitor changes in cycling traffic flow as the BSS evolves, so we will be able to evaluate the impact of the system's growth (both in extension and in terms of increasing the BSS stations' density) as well as the impact of the implementation of new infrastructure or policies. In addition, it would be of interest to monitor the evolution of the amount of cycling flow supported by the cycling infrastructure, and compare it to the existing flow in other case studies.

The pulse of the cycling city:

Visualizing Madrid Bike Share System GPS routes and cycling flow

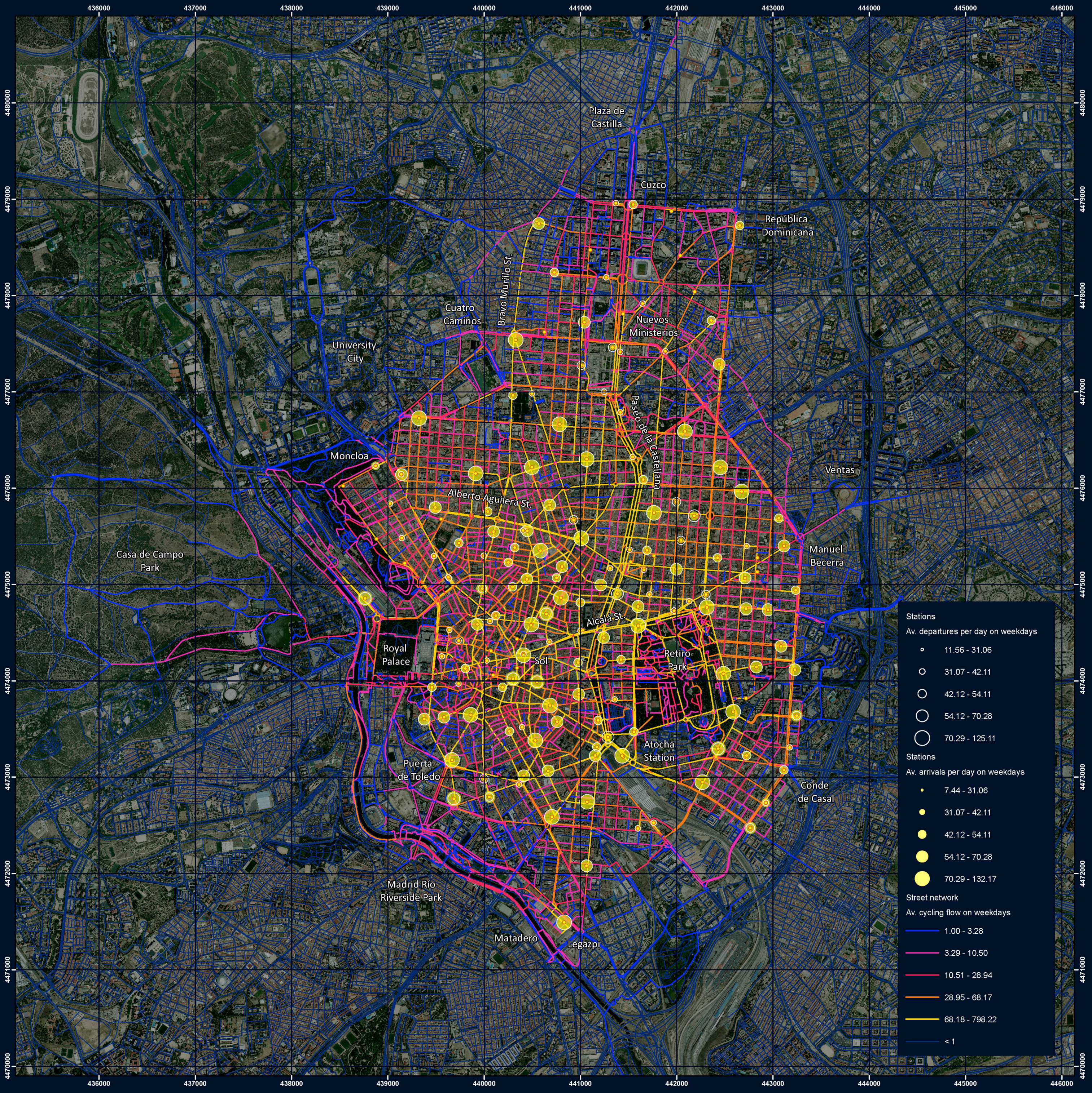
Cycling flow on a working day

These maps show the cycling flow from Madrid Bike Share System (BiciMAD) activity at different moments, obtained by processing over 250,000 GPS routes collected by the system in April 2017. The map on the left shows the average cycling flow on a workday. The street segments are represented according to the average cycling flow, assigned by summarizing the number of total trips while overlapping each street segment over the month's working days, divided by the number of working days in April. The map provides us with an overall view of the cycling footprint and its extension across the city network, so we can identify the most important arteries in terms of cycling flow.

Representation of activity at BSS station level, by aggregating the number of departures and arrivals at each station, provides for better understanding of BSS flow. This is because the most important cycling streets clearly connect the most relevant stations. The overlapping circles provide information on the balance or imbalance of stations in terms of attraction and generation of trips.

Table1: Basic route statistics according to different periods of time and type of users

Target routes	Av. Speed (kph)	Av. Distance (m)	Av. Time (min)	Count
Total routes	14.06	3,103.94	17.13	226,253
Type user 1 (Frequent user)	14.29	3,011.47	15.90	212,012
Type user 2 (Occasional user)	8.59	5,518.03	48.49	4,279
Weekday routes	14.35	2,992.70	15.79	158,246
Weekend routes	13.44	3,256.27	19.34	49,700
Easter routes	13.24	3,651.94	22.71	18,307
Basic route statistics of frequent users during weekdays over the course of the day				
7-10h	15.71	2,961.96	13.82	28,002
13-16h	13.78	3,166.50	17.92	41,246
22-01h	14.62	2,832.82	14.56	27,124



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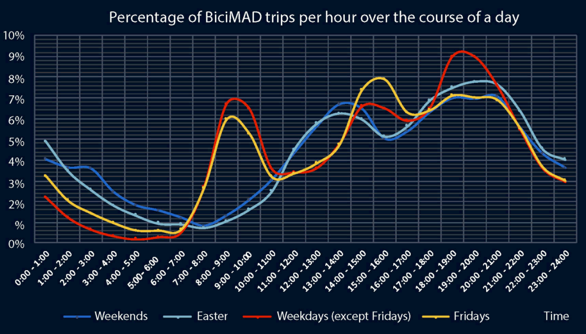
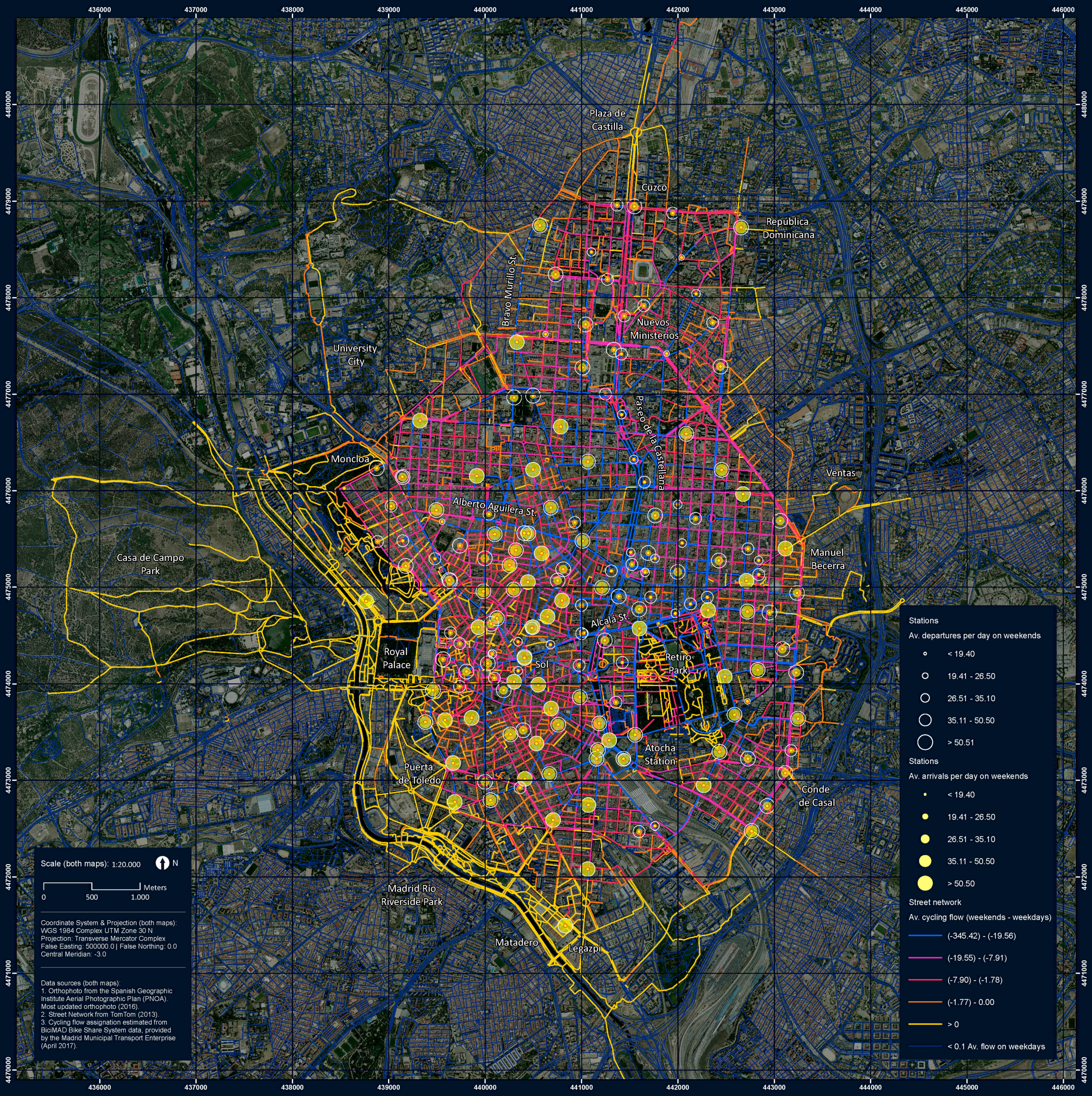
Cycling flow on a weekend day

This map focuses on representing the difference between cycling flow on weekends and weekdays. For each street segment, it shows the difference between the average cycling flow on a weekend day and the cycling flow on a workday. Yellow lines show positive values; in other words, street segments where there is a greater cycling flow on weekends than on workdays. The other colours show negative values (streets with less activity during weekends). The overall footprint reveals significant differences, such as increased cycling flow in the city's most important parks, including Madrid Rio, the riverside park, the Casa de Campo, and some areas of El Retiro. Other areas show radically decreased activity (in dark blue), such as the north-south axes Paseo de la Castellana and Bravol Murillo, some of the most important on weekdays.

The activity at station level also bears remarkable differences, with a high concentration of activity at stations around the city centre, and less activity around the Paseo de la Castellana, which is more connected to the city's financial and business centres.





5 Collecting, visualizing and analysing casual cyclists and bike messengers’ routes: The Initiative Madrid Cycle Track (Huella Ciclista de Madrid)

Remarks

This section is based on the research titled "*Madrid cycle track: Visualizing the cyclable city*" (Romanillos & Zaltz Austwick, 2016), published in Journal of Maps as part of this thesis. The research provides an analysis of casual cyclists' routes according to the purpose of the journey, the average speeds, distances, travel times, accumulated elevation gain, the type of bike used and also compares the results to the ones obtained with bike messengers.

Access to paper: https://www.tandfonline.com/doi/abs/10.1080/17445647.2015.1088901

5.1 Introduction

The understanding of urban cyclist behaviour is crucial to planning and designing optimal bike infrastructures and promoting efficient policies aimed at fostering cycling as a sustainable mode of transport in cities. Cyclist behaviour is complex and not easily predictable because it's influenced by a diverse set of factors. With different objectives, it has been traditionally analysed through the information derived from household surveys or more specific group surveys. Regarding the areas of demand analysis, preference evaluation and forecasting, Stated Preference (SP) techniques have been commonly applied (for example, Kroes & Sheldon (1988)), in order to measure the effects of certain improvement on cycle facilities and then forecast the effect of others (Hopkinson & Wardman, 1996) or with the aim of estimating the potential cycle demand in certain urban areas (Ortúzar et al., 2000). Also Revealed Preference (RP) studies have been conducted with different purposes, such as the development of mode choice models (Noland & Kunreuther, 1995).

More specifically, concerning the spatial analysis of cycling for planning purposes, Stated and Revealed Preference methods have been the dominant techniques. In SP studies, respondents were typically asked to evaluate the impact of different factors on their cycle route choice, or to state their preference for a street or a route by evaluating the options using photos of the routes or locations (Bradley & Bovy, 1984; J. Larsen & El-Geneidy, 2011; Tilahun et al., 2007). Some RP based studies asked respondents to design their cycle route on a map (Ben-aiuva & Morikawa, 1990) and finally, some approaches involved both SP and RP techniques but still using similar methods (Yang & Mesbah, 2013).

In recent years, the research on cycling has grown substantially, and shifted with the emergence of new location-based data allowing more complex spatial analysis. Recent investigations have studied two different types of location data: point data captured by the growing Bike Share Systems spread around the world (Etienne & Latifa, 2012; Froehlich et al., 2009; O'Brien et al., 2013; Zaltz Austwick et al., 2013b) and GPS tracking data collected through smartphones applications or specific devices, gathered specifically with research purposes or made available by "Big App" Companies for research or planning (Broach et al., 2011; Harvey & Krizek, 2007; Menghini et al., 2010).

By overcoming the traditional SP and RP limitations in terms of high costs, small samples and spatial imprecision (Hood et al., 2011), these new studies are improving the understanding of urban cyclist behaviour and producing outputs to inform the planning and design of bike infrastructures and policies.

This goal of this study is to describe the objectives, the methodology and the outputs of the initiative *Huella Ciclista de Madrid* (Madrid Cycle Track), launched with the aim of collecting cycling routes and other information from volunteers in the city of Madrid, as well as to present the resulting map –and its online version –that represents all the gathered cyclist routes. Finally, cyclist flow over the course of a day is visualized through a supplemental video.

5.2 The Initiative Madrid Cycle Track: Collecting cycling routes

5.2.1 Background and main objectives

Madrid Cycle Track (originally *Huella Ciclista de Madrid*, in Spanish) launched in June 2013 in the framework of a broader research aimed at developing new models for designing optimal bike networks, in which the understanding of cyclist behaviour and route preferences plays a crucial role. In this domain, modelling is targeted to forecast the potential cyclist flow in different bike network proposals, evaluating the impact of different factors on cyclists' route choice (such as the slope of the streets, the type of bikeway, or traffic density) as well as disaggregating cyclists by factors such as age or gender or journeys purpose. In order to perform this evaluation, an analysis of real cyclist routes in Madrid (the research case study) was required.

The available information on Madrid bike mobility was limited to the Transport Household Survey conducted in 2004 and other more specific surveys aimed at analysing the evolution of cycling in certain areas of the city in which bike infrastructure has been implemented. Because these surveys did not provide relevant spatial data for the purpose of the investigation, the research team conceived the initiative *Madrid Cycle Track* with the aim of gathering cyclist routes and other relevant data from volunteers in the city of Madrid.

5.2.2 The online platform and the participation process

The initiative was launched through an online platform (Figure 5.1), available at www.huellaciclistademadrid.es. I designed with five different objectives. The first one was to disseminate the initiative and provide information about the project's background and goals, so that potential volunteers could get interested on it. In order to disseminate better the initiative among the different local cycling associations, I also made use of different social networks (such as Facebook or Twitter) and a promotional video was also created in order to present the initiative in a more attractive way. An important effort was necessary in order to get cyclists attention, interest and eventually, participation.

Figure 5.1: Screenshot of the Huella Ciclista de Madrid online platform

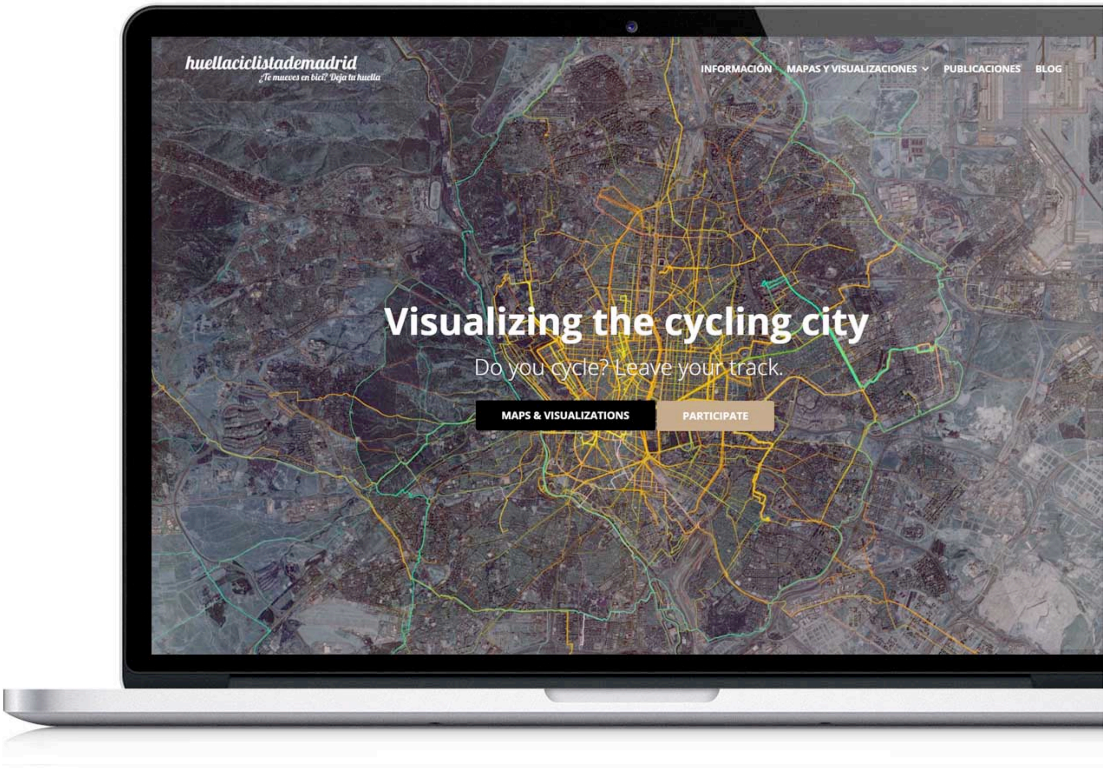
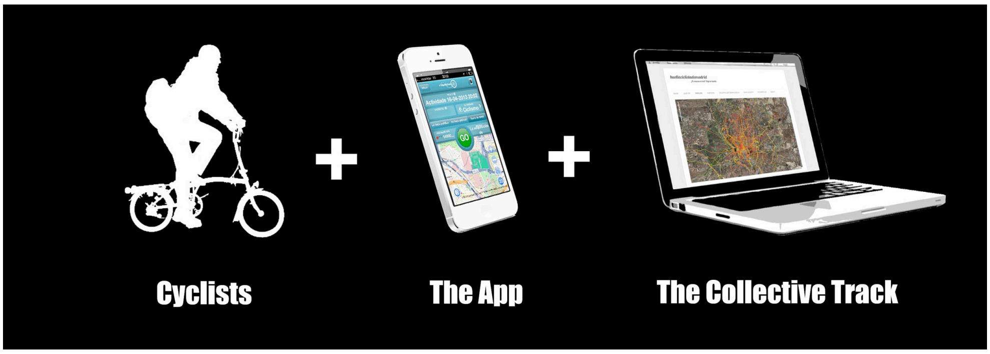


Figure 5.2: Screenshot of the Huella Ciclista de Madrid promotional video

The second goal was to enable the engagement of urban cyclist interested in the initiative. Volunteers could registered, download a free GPS smartphone application, Map My Tracks, and join the group of volunteers within the online platform to make the process minimize the risk of volunteer drop-out.

Figure 5.3: Illustration representing the initiative workflow

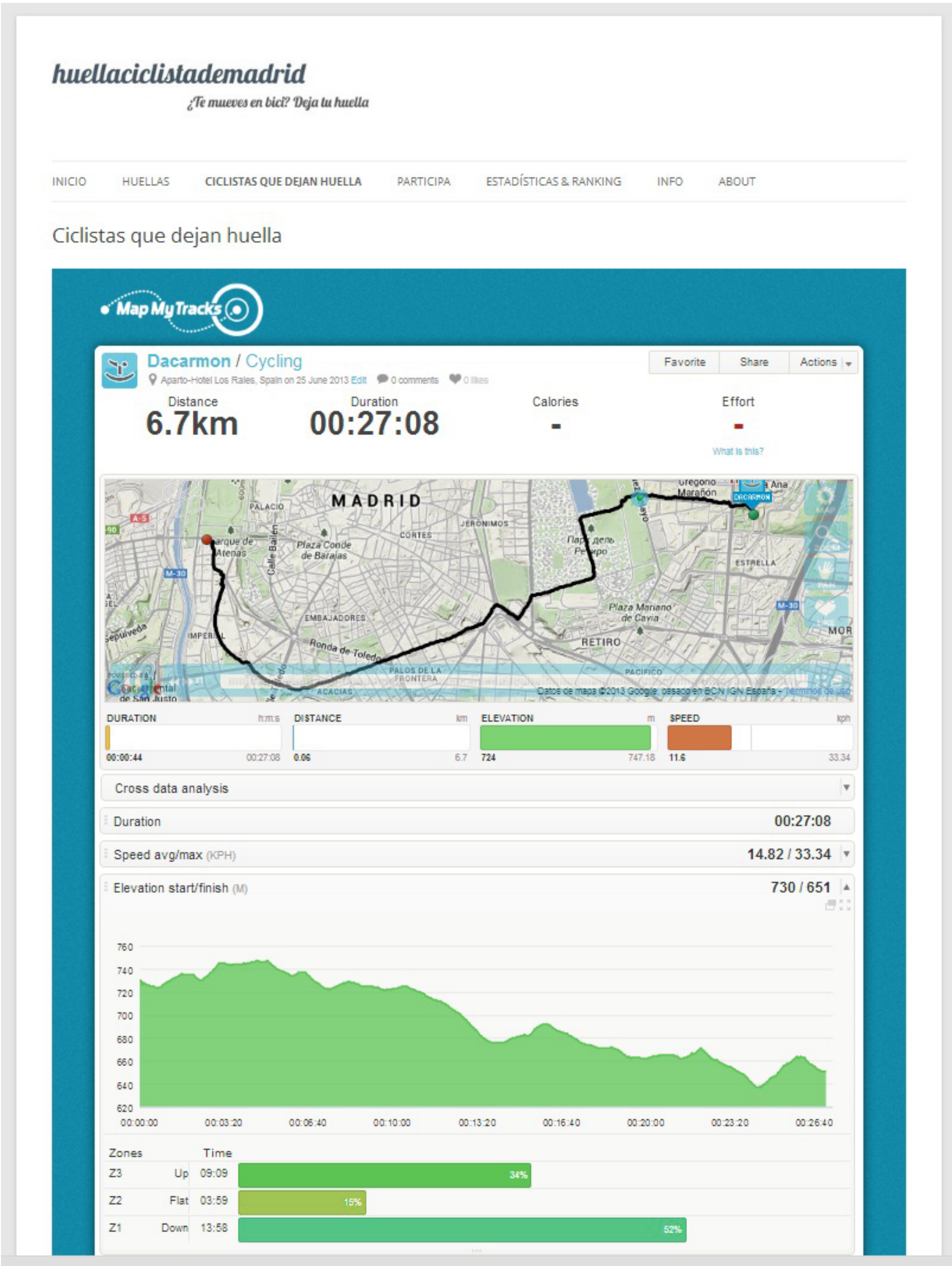


The third and main objective of the online platform was to collect cyclists' routes. Volunteers could upload the routes to the platform in three different ways. Initially, cyclist could only participate by uploading routes through the smartphone GPS app. All of the data was stored in the app website and then downloaded by the research team. In a second stage of the project, due to volunteer demand, the gathering process let cyclist to upload GPS that they collected through other GPS apps. The number of cyclists participating through this option was not very high, but was easily implemented and provided some extra GPS tracks. Finally, in order to open the initiative to people not owning a smartphone or not willing to use the app for whatever reason, a participative online map was embedded on the platform enabling volunteers to easily design their cycle routes on a map with accuracy and with the possibility of providing some extra information about themselves (like age and gender) and their routes (like purpose and frequency of the journey or safety of the route).

Figure 5.4: Image of the flyer distributed in Madrid during the promotional weeks of the initiative

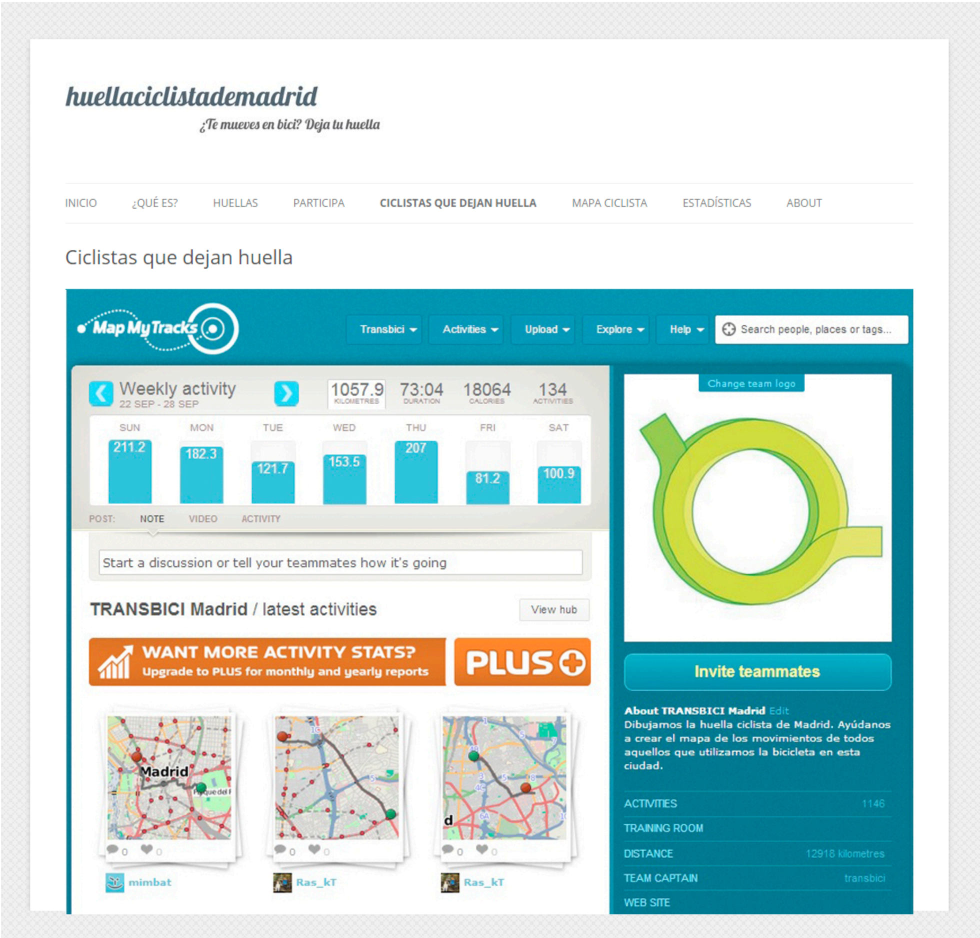
The fourth goal was to let cyclist visualise their routes, get access to different statistics and explore some data about their activity (distance and time travelled, gradient, slope, speed, etc.). Volunteers could also look up other group members' activity and get in touch with them by text messages. These functionalities provided the sense of belonging to a community, and encourage people to participate and to invite other people to join the initiative. Figure 5.12 shows a screenshot of the online platform illustrating collected cyclists' routes.

Figure 5.4: Screenshot of the online platform illustrating collected cyclists' routes



Finally, the fifth objective of the online platform was to visualize the *collective cycle track* through different online maps that represented the evolution and the growth of the track over time. The representation of all the routes together through online maps let the possibility of exploring the city, visualizing the streets with highest levels of cyclist flow according, for example, or relating routes to journey purpose. However, providing appealing feedback to the volunteers that altruistically participated on the initiative was a goal in itself. They could not only visualise the collective track but to identify and look up individual contributions by clicking on the routes. These online maps are described in more detail in later sections.

Figure 5.5: Screenshot of the online platform illustrating collected cyclists' routes



5.2.3 Bike messengers engagement

Bike messengers companies are experiencing a renaissance, playing a growing role in the delivery of packages and mail in many major cities (Fleming, 2012a; Hong, Wei, & Wei, 2006; Kidder, 2008). Cycle couriering is a competitive transport mod for the delivery of time-sensitive materials in the core of many metropolitan areas (Kidder, 2008, 2011), but also is attractive from a sustainability perspective. Many cities are implementing policies aimed at fostering this sustainable transport system in urban areas (Fleming, 2012b; Hong et al., 2006). In this sense, the study of bike messengers' mobility could provide some relevant clues for better implementing these planning and policy strategies. However, while bike messengers have been studied from the social research field (Fincham, 2007; Kidder, 2011) or regarding environmental questions (Bernmark et al., 2006), their mobility is underexplored and has not been spatially analysed (with few exceptions, for example (Kidder, 2008)), in comparison with casual cyclists or other transport modes.

The city of Madrid is not an exception and several new bike messengers companies emerged recently. Our interest for studying and comparing their mobility patterns with the one of casual bikers for which we had started collecting data led us to open the Madrid Cycle Track initiative to their participation. On November 2013, four different companies based in Madrid joined the initiative and started to track their activity: *Emakers, Trébol ecomensajeros, Mensos and BikePost ecomensajeros*.

Figure 5.6: Illustrations on the web announcing the participation of bike messengers

Though the bike messengers' activity was eventually integrated in the existing online platform, the methodology followed to collect their routes differed from the one followed with casual bikers. Since couriers cycle many hours a day and often use their phones with working purposes, smartphone GPS app have serious issues around battery life. Instead, these companies were equipped with specific cycling GPS devices (Garmin EDE 200). Their tracks were initially uploaded to a Garmin online platform (Garmin Connect), and then downloaded and integrated in the online platform of Madrid Cycle Track, where they were visualized through an independent online map, similar to the one displaying casual bike mobility.

5.2.4 Results

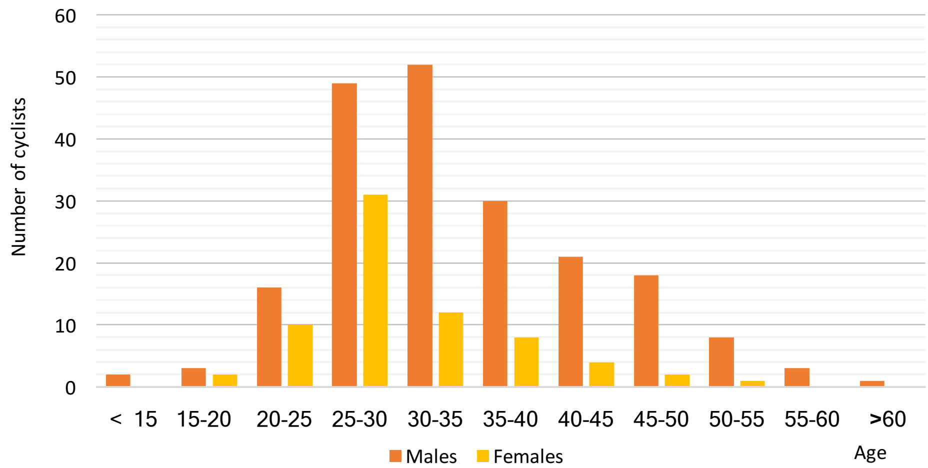
6,022 cycle routes were gathered, resulting in 48,122 km of tracks uploaded by 328 volunteers participating from June 2013 to September 2014, including both casual cyclists and bike messengers.

Taking into account that cycling modal share in Madrid is estimated to be around 1,20%, according the data collected from different sources by Kisters, García, Rondinella, & Alduán (2016), and the percentage of cyclists of the total population of the municipality of Madrid (3,165,000 habitants in 2014) is estimated to be the same, the sampling error that corresponds to our sample, considering a statistical confidence level of 95%, is 5.4%.

5.2.4.1 Casual cyclists results

Casual cyclists' routes were mainly collected from June 2013 to March 2014, after a two-month period of gathering routes for testing the app and the online platform performances. The initiative collected 37,345 km of cycle routes obtained from 3,970 journeys. From them, 327 were gathered through the "Design your route" map, and the rest are GPS tracks collected through the online, with 307 participants in total. The proportion of males and females in this sample was 72%-28% respectively, figures that correspond well to existing local surveys (DOYMO, 2011; Monzon de Cáceres et al., 2011). Figure 5.7 illustrates the gender proportion according to age.

Figure 5.7: Number of cyclists according to age and gender



The data obtained from the routes revealed differences in average speed, distance and travel time, according to the purpose of the journey. Table 5.1 shows summary statistics regarding this. The average speed data of this table have been updated in relation to those published in Journal of Maps, after map-matching the GPS track lines to the network, being now more accurate.

The sample collected through the Madrid Cycle Track initiative has also been checked in terms of the share according to the different purposes of the journey, by comparing the percentage of the data collected to the ones of the last household travel survey conducted in Madrid (Consorcio Regional de Tranpsortes de la Comunidad de Madrid, 2014). Figure 5.8 shows that, essentially, the different percentages of trips according to the purpose of the journey match, with the exception of sport, which is not included in the Madrid household travel survey. The most important difference is found in the overrepresentation of cycling leisure trips, something that can be found normal and expected when considering the use of bikes

Table 5.1. Route statistics according to the purpose of the journey

Purpose of the journey	Routes (%)	Routes* (%)	Speed Av. (km/h)	Time (min) Average	Distance (m) Average
Commuting	31.11	42.19	15.75	24.52	5,889
Leisure	17.17	23.28	15.29	23.94	5,705
Sport	5.72	7.76	15.87	80.81	21,002
Shopping	6.30	8.55	13.92	22.29	5,648
Errands	5.51	7.47	15.18	17.07	4,231
Study	7.93	10.76	15.07	21.12	5,201
Unknown	26.26	-	14.21	28.30	6,638
Total/Mean over total	100.00	100.00	15.03	31.64	7,947

* Routes over total number with known purpose

he sample collected through the Madrid Cycle Track initiative has also been checked in terms of the share according to the different purposes of the journey, by comparing the percentage of the data collected to the ones of the last household travel survey conducted in Madrid (Consorcio Regional de Tranpsortes de la Comunidad de Madrid, 2014). Figure 5.8 shows that, essentially, the different percentages of trips according to the purpose of the journey match, with the exception of sport, which is not included in the Madrid household travel survey. The most important difference is found in the overrepresentation of cycling leisure trips, something that can be found normal and expected when considering the use of bikes.

A more detailed insight into cycling routes according to travel distance allow us to uncover some important travel patterns, such as the important imbalance when considering gender, as Figure 5.9 shows, representing the percentage of commuting trips according to distance and gender. The average travel distance is 6.267 m and 4,535 m for males and females respectively, figures that evidence that males' average travel distance is a 32% greater than females'. Females' graph experiment a dramatic drop after reaching 5,500m, presenting a more asymmetric curve than males.

Figure 5.9: Percentage of commuting trips according to distance

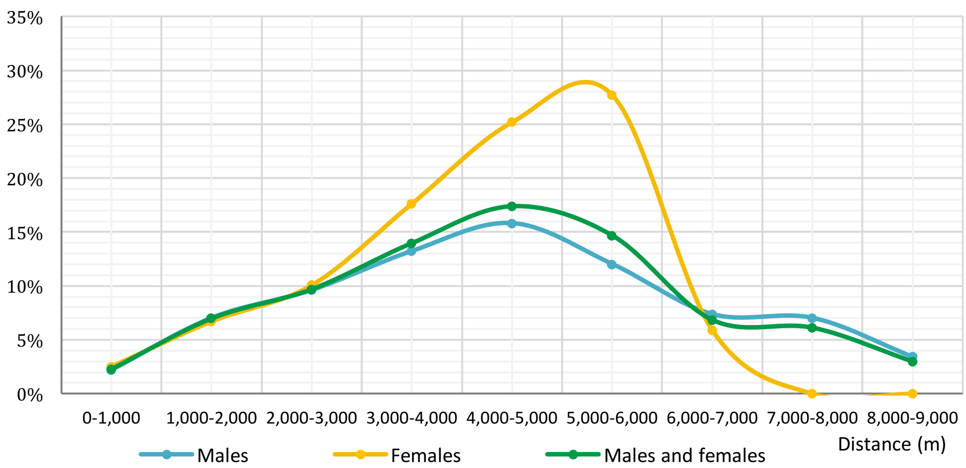
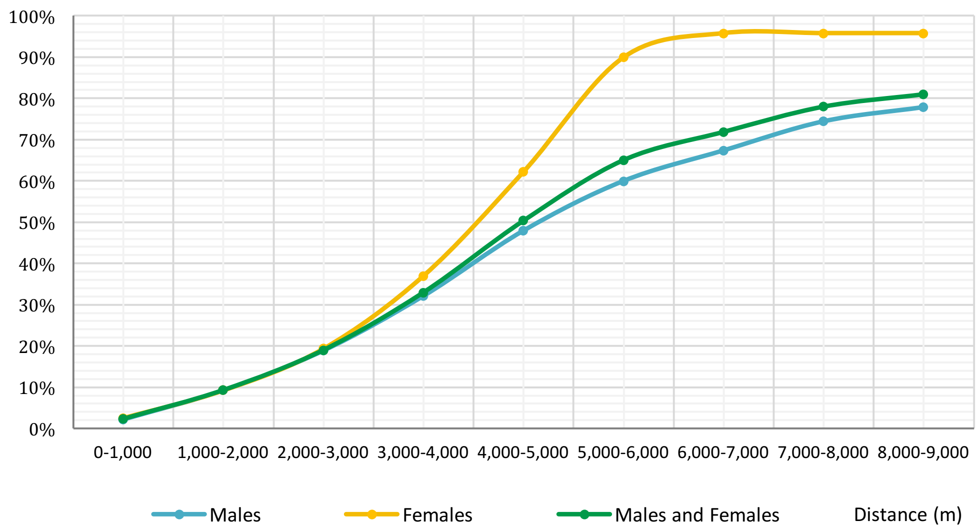


Figure 5.10 illustrates the percentage of accumulated trips according to distance and considering gender as well. The graph highlights the differences between males and females, especially after 3,500 m distance, when both curves begins to diverge. 90% of females' trips are under 5,500 m while at this distance correspond to the 60% of accumulated males' trips, a variation of a 50%.

Figure 5.10: Percentage of accumulated trips according to distance



Finally, the main map (attached at the end of this section) showing all the routes together yields clear mobility patterns to the trained eye. For example, the business districts spread along the Castellana axis and the employment associated with it explains a high volume of commuter cyclists; journeys around the University Campus may include trips with mixed purposes such as leisure, sport, commuting and study; other areas such as the *Casa de Campo* park, the *Madrid Río* riverside park or the *Cycling Belt* present mainly leisure and sport journeys.

A surprising finding when exploring the map is the fact that streets with high level of motor traffic are used by a significant number of cyclists. Past surveys report that intensive traffic is one of the most significant barriers to cycling, especially for non-cyclists considering adopting cycling (Monzon de Cáceres et al., 2011). Finally, at a neighbourhood scale, some other interesting patterns can be identified; for example, the influence of the slope in hilly areas of the city, evidenced by the use of different streets when going up or down on similar routes.

5.2.4.2 Bike messengers results

Bike messengers' routes were collected from November 2013 to September 2014, though the companies participated in different moments throughout this period of time. 2,052 routes were gathered from four different companies, providing 10,777 cycled kilometres. The total number of cyclists participating in the initiative was 23. After a cleaning process, some routes were discard (due to other possible purposes rather than couriering) and finally the route sample we analysed and visualised was composed of 1,722 routes and 9,143 km. Bikers' socio-demographic data were not provided by the companies, though their profile was similar: all were male and aged between 18 to 42.

Three different type of bikes were used by the messengers. Depending on the volume and weight of the material to deliver, apart from *casual bikes*, they rode *bullit cargo bikes* (or freight bikes) and *cargo trike bikes* (or freight tricycles), though the sample gathered includes very few of the latter. Some of the bullit cargo bikes and the cargo bikes featured electric assistance.

The resulting map illustrates different mobility patterns compared to the ones obtained from casual bikers. The map illustrates that the main streets of the city, often those presenting highest values of vehicle traffic density, showed also the maximum cycle flow values, evidencing that bike messengers are more used and less afraid of coping with vehicles. The video visualisation also evidences the different flow patterns over the course of the day, almost complementary. Casual cyclists' performance shows the classical two peaks, early in the morning and then in the evening, and bike messengers' activity is more distributed throughout the morning and afternoon.

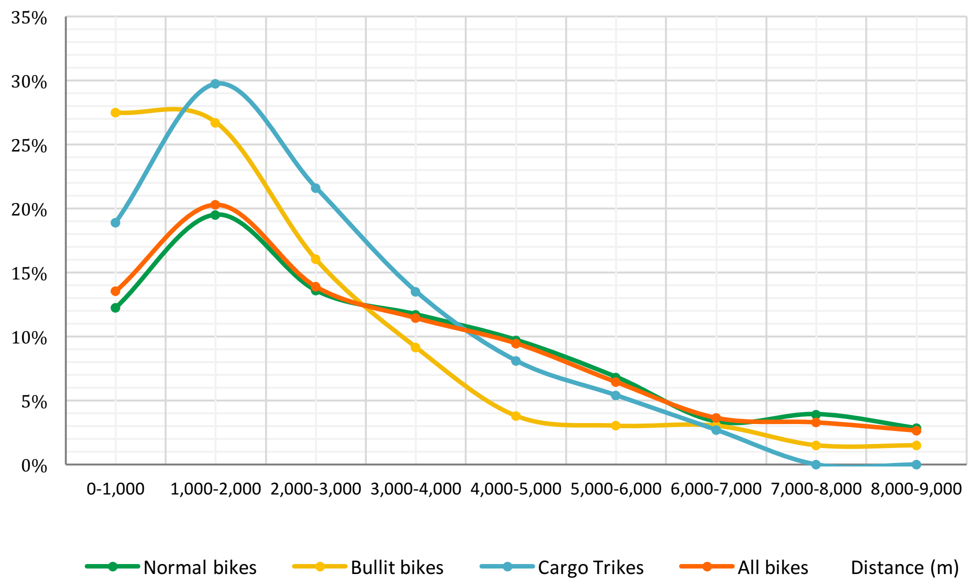
Finally, the analysis of the data derived from the GPS tracks revealed some interesting and also unexpected findings on bike messengers' behaviour. Though it is not the objective of this research to describe them in detail, some interesting outcomes can be highlighted. It was expected that the average speed of messengers riding casual bikes (19.6 km/h) was higher than those of casual cyclists (15.42 km/h), but we found surprising that the average speed of messengers riding bullit cargo bikes is revealed as similar (19.7 km/h) to the one of messengers riding casual bikes. In this particular case, this finding can be due to the electric assistance that most of the bullit cargo bikes features, and the way it helps messengers in a hilly city like Madrid. Though they are also electrically assisted, the average speed of cargo trike bike was notably lower than the other ones (11.4 km/h). Other variables, such as the average distance or the height gradient of the journeys, showed also clear differences. Table 5.2 illustrates some basic statistics on bike messengers mobility according to the type of the bike used.

Table 5.2. Cycling statistics according to the type of bike of the messengers

Type of Bike	Routes (Count)	Average Speed (kph)	Average Gradient (m)	Average Time (min)	Average Distance (m)
Normal bike	1,553	19.6	95.8	30.49	5,245
Bullit bike	131	19.7	63.7	11.26	3,061
Cargo trike	37	11.4	134.1	14.85	2,494

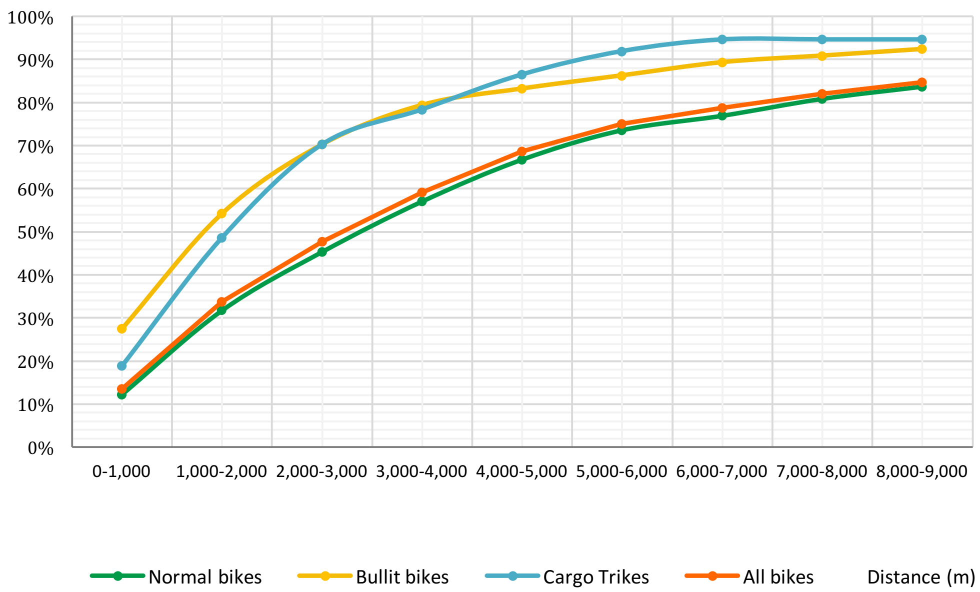
The analysis of bike messengers' trips according to distance reveal important differences between when distinguishing the three types of bikes used by the companies. Figure 5.11 shows the different curves that illustrate the percentage of trips according to distance and type of bike. According to the graph, bike messengers use *bullit bikes* and *cargo trikes* (the ones that allow them to carry the most heavy and voluminous parcels) for the shortest trips, with significant higher values for routes under 1km and between 1 and 2km, than the ones that correspond to normal bikes.

Figure 5.11: Percentage of bike messengers' trips according to distance



A complementary analysis of bike messengers' accumulated trips according to distance confirm more clearly this trend. Approximately 90% of the trips that correspond to bullit bikes and cargo trips cover distances under 5.5 km, while the percentage of accumulated trips that correspond to normal bikes is around 75%.

Figure 5.12: Bike messengers' accumulatd trips according to distance



5.2.4.3 Comparing casual cyclist, bike messengers and BiciMAD routes

Casual cyclists, bike messengers and BiciMAD users show very different patterns regarding average trip distances. Figure 5.13 illustrates the percentage of trips according to distance for each of these groups, considering weekdays' journeys in the case of BiciMAD and commuting trips in the case of casual cyclists, in order to make a more reasonable comparison (occasional BiciMAD users have very different travel patterns as we have previously seen and represent a minority of the group). Figure 5.14 provides a complementary graph by representing cyclists' accumulated trips according to distance.

Figure 5.13: Percentage of trips according to distance

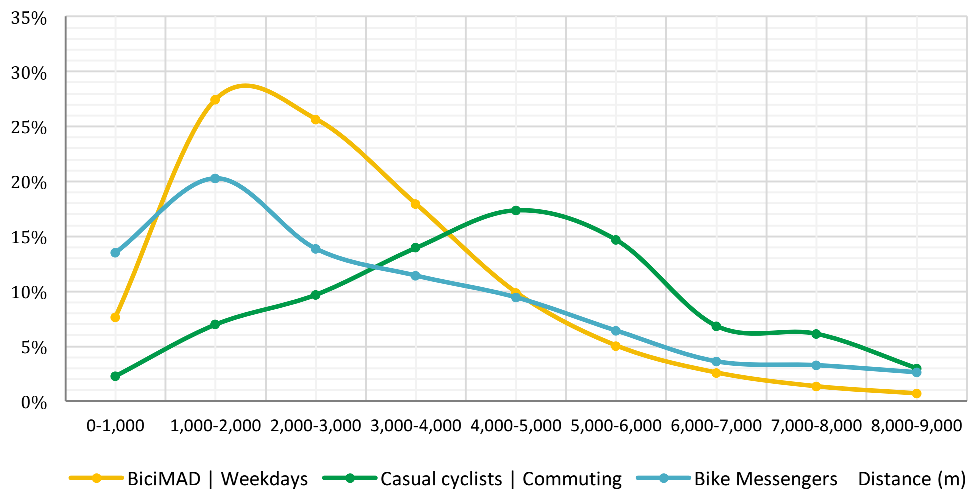
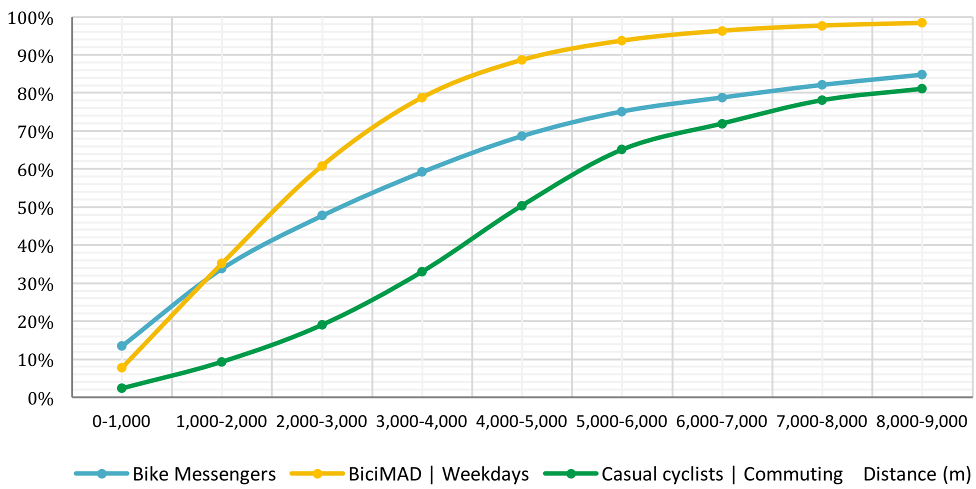


Figure 5.14: Percentage of accumulated trips according to distance



Regarding bike messengers, Figure 5.13 shows that the highest concentration of their trips are between 1 and 2 km, although the graph goes slightly down with an small but significant percentage of trips (approximately 30%) over 5km length, as Figure 5.14 reveals. This graph somehow reveal what is the 'operational range' of distance of bike messengers' companies, which in many cases do not have only one distribution point but many in the cities where they are implemented.

When it comes to casual cyclists commuting routes according to distance, the average distance is 5,889 m (see Table 5.3). Figure 5.13 evidence that the maximum concentration of trips corresponds to distances between 3 and 6 km, average distances considerably higher than the ones of the other groups. In addition, more than a 20% of trips correspond to journeys over 9 km length.

Finally, regarding the analysis of BiciMAD frequent users routes on weekdays, the average distance is 2,935 (see Table 5.3), and the highest percentage of trips correspond to the ones that are approximately 2 km length (Figure 5.13), although in this case the graph goes down more dramatically, with just a 10% of trips over 5 km length (Figure 5.14). Although a recent study conducted by Castillo-Manzano, López-Valpuesta and Sánchez-Braza (2016) also uncovered significant lower distances in Public Bike Sharing Systems trips than in private bicycles trips in the case of Seville, and pointed to a possible general trend in other cities for different reasons, the difference found in Madrid (almost 2 km) are much greater than in Seville (between 0.724 and 0.805 km) might be caused by the limits of the area currently covered by BiciMAD, and the expansion that will be taking place in the near future probably will change this pattern.

In addition to analysing the different groups of cyclists considered in thesis according to travel distance, we have analysed these groups' cycling operating speeds, obtaining some remarkable findings.

The first one is that, contrary to popular belief, BiciMAD users' speeds are not higher than casual cyclists' speeds, but slightly lower. As Table 5.3 shows, BiciMAD frequent users' average speed is 14.29 kph while casual cyclists' one is 15.03 kph. However, both cyclist groups show quite similar circulating speeds when considering commuting trips: BiciMAD users' average speed during weekdays, between 7-10h, is 15.71 kph while casual cyclists' average speed is 15.75 kph when considering commuting as the purpose of the journey. This finding may result surprising if we consider that all BiciMAD bikes are e-bikes, a fact that could influence positively cyclist's average speeds, even considering that the bikes electric assistance is interrupted when cyclists reach 25 kph. A possible explanation is that, leaving aside the 'physical condition' factor (because of the electric assistance), some BiciMAD users might not have the experience and familiarity of regular casual cyclists, so they ride at lower speeds. This could be the case especially considering that the volunteer cyclists joining the *Huella Ciclista de Madrid* initiative could correspond to a more compromised and experienced cyclist profile, related to the cycling associations that supported the initiative.

Another finding, not surprising at all in this case, is that bike messengers' speeds are clearly higher than casual cyclists' and BiciMAD users' one, as Table 5.3 illustrates. Bike messengers show the highest average speed found among all cyclist groups, with 19.60 kph and 19.70 kph when riding normal bikes and the increasingly common bullit bikes, respectively. However, this is not the case when using cargo trikes, with an average speed of 11.40 kph. Bike messengers' average speed is even higher than the one of casual cyclists considering sport as the purpose of the journey (15.87 kph), a fact that may result unexpected. However, it is important to take into account that the extension that we have covered with the Huella Ciclista de Madrid is the essentially Madrid municipal area, and in consequence, we are not including but a small sample of sportive cyclists activity, and most of them are mountain bikers (in the Casa de Campo park, for instance), rather than road sportive cyclists. Most of the cyclists belonging to this last group is concentrated in the so called “anillo verde ciclista” or “green cycling belt”, a peripheral bike lane around central Madrid, clearly visible on the main map, attached at the end of this section.

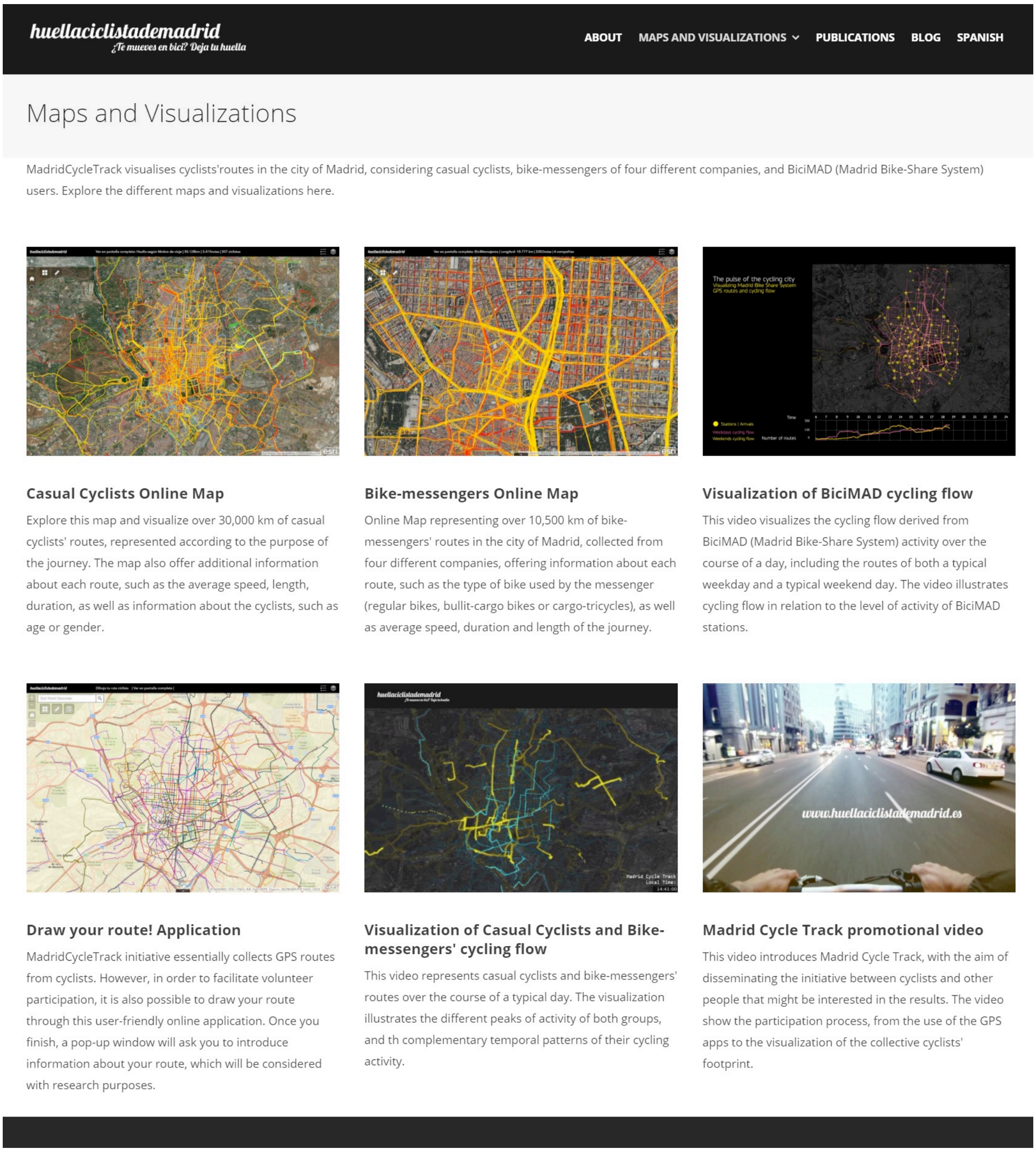
Table 5.3. Casual cyclists, bike messengers and BiciMAD users' routes statistics

Casual cyclists' routes according to the purpose of the journey			
Purpose of the journey	Average Speed (kph)	Average Time (min)	Average Distance (m)
Commuting	15.75	24.52	5,889
Leisure	15.29	23.94	5,705
Sport	15.87	80.81	21,002
Shopping	13.92	22.29	5,648
Errands	15.18	17.07	4,231
Study	15.07	21.12	5,201
Average regardless purpose	15.03	31.64	7,947
Bike messengers' routes according to the type of bike used			
Normal bike	19.60	30.49	5,245
Bullit bike	19.70	11.26	3,061
Cargo trike	11.40	14.85	2,494
BiciMAD users' routes according to different periods of time and type of users			
Type user 1 (Frequent user)	14.29	15.90	3,011
Type user 2 (Occasional user)	8.59	48.49	5,518
Weekday routes	14.35	15.79	2,993
Weekend routes	13.44	19.34	3,256
Easter routes	13.24	22.71	3,652
Weekday Frequent users	14.51	14.96	2,935
Eastern Occasional users	8.81	49.05	5,940
Weekends occasional users	8.55	49.97	5,641
Weekends frequent users	13.76	17.57	3,120
BiciMAD route statistics of frequent users during weekdays over the course of the day			
7-10h	15.71	13.82	2,962
10-13h	13.20	20.09	3,280
13-16h	13.78	17.92	3,167
16-19h	13.70	18.89	3,305
19-22h	13.50	17.10	3,049
22-01h	14.62	14.56	2,833
01-07h	15.53	14.74	2,874

5.3 The online maps

The *Madrid Cycle Track* web platform (www.huellaciclistademadrid.es) hosts different online maps aimed at illustrating both the casual cyclists' and the bike messengers' routes, and its evolution over time. All the online maps have been designed using the *ArcGIS Online* platform. They are finally embedded in different pages of the website (a *WordPress* blog) using *iframes*. In order to better configure the presentation of these maps within the website, we have used the *Web Maps for WordPress* and the *iframe* plugins.

Figure 5.15: Screenshot of the Maps and Visualization page on the website (Link to web).



The use of online maps offers many advantages. Because of the different functionalities they provide, they are more dynamic, more complete and easier to explore than conventional printed or digital maps. It is possible to change the extent and the scale of the map, so that we can have an idea of the global cyclist track (Figure 5.16) as well as to explore the cyclist flow in specific streets. We can select different base maps (provided by ArcGIS Online or other Web Maps Services) or search for specific locations. We also have access to information regarding the routes and the cyclists behind them. By selecting any track, a pop-up window emerge (Figure 5.18) showing different data such as the name (username), age and gender of the cyclists, or the purpose of the journey, distance travelled, average speed, time, gradient, etc. This functionalities made the map attractive not only for the cyclist community participating in the project but also for other people interested in exploring bike mobility in Madrid.

Finally, the initiative was released to people not owning a smartphone through the "Design your route map" (Figure 5.18), another online map opened to public edition. Volunteers could easily design their own cyclist route on the map, using the base maps and the zoom for more accuracy, and once finished, they could introduce some personal information (username, age and gender) as well as some other information regarding the route (purpose, frequency, safety, etc.). This map was also designed using ArcGIS Online platform. This map is accessible at the website, through the label *Mapas y Visualizaciones/Dibuja tu ruta!* in the Menu bar.

Figure 5.16: Screenshot of the online map illustrating casual cyclists' mobility (Link to web).

Figure 5.17: Screenshot of the online map illustrating bike messengers mobility and a pop-up window with information about the selected route ([Link to web](#)).

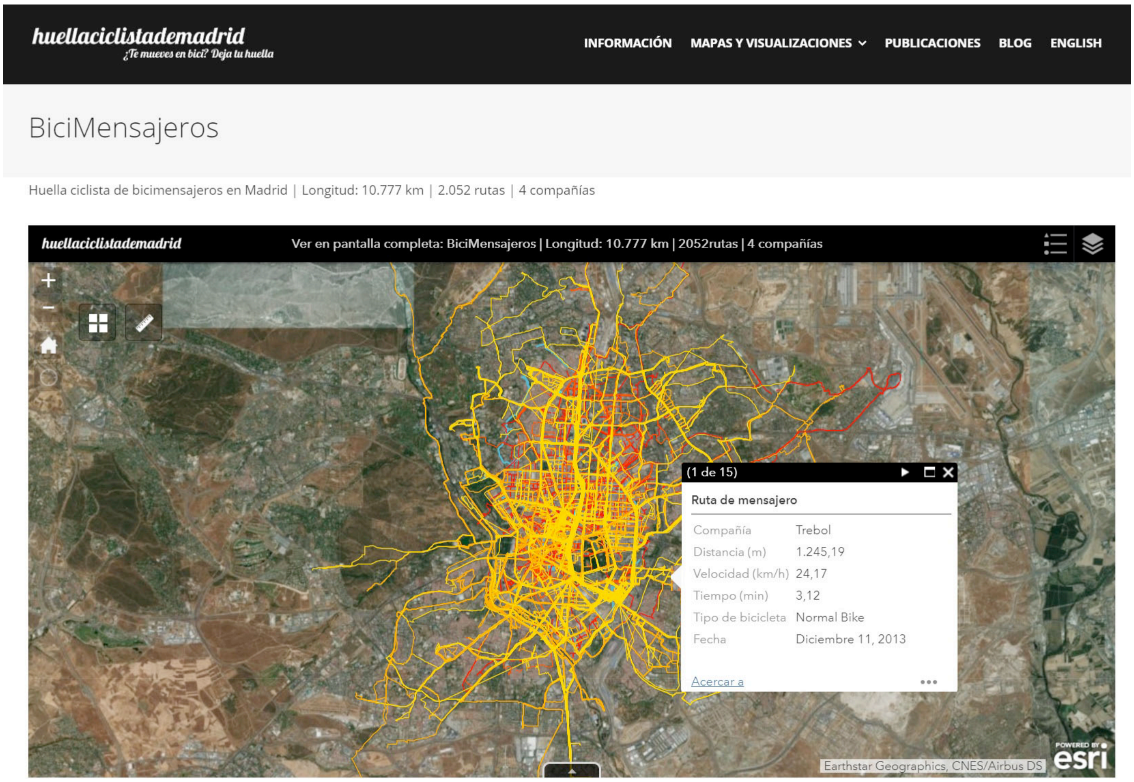
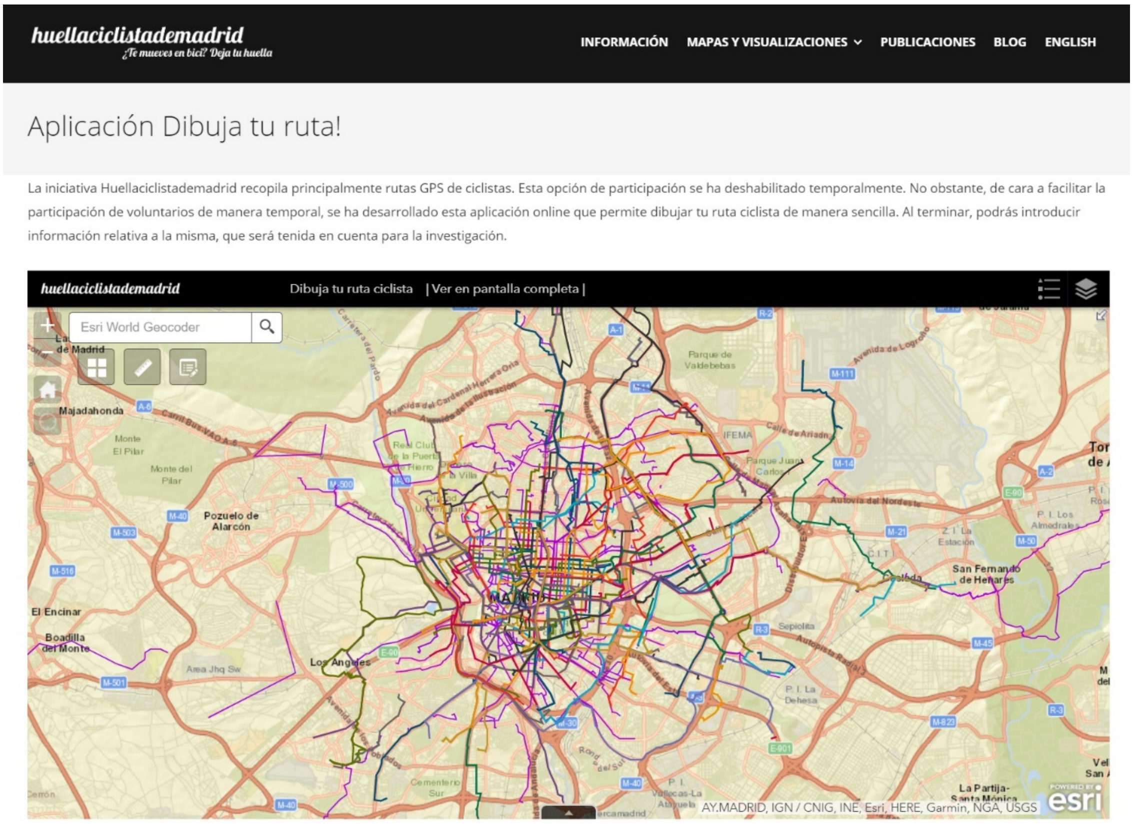


Figure 5.18: Screenshot of the "Design your route" online map ([Link to web](#)).



5.4 The map

The map canvas illustrates both the casual cyclists' and the bike messengers' collected routes through four different maps. The first map represents casual cyclist mobility on a map at a metropolitan scale. Routes are symbolized according to the purpose of the journey, distinguishing between work-commuting, study, shopping, leisure, sport and others, so that it is possible to visualize not only overall cyclist flow but the spatial patterns that emerge regarding the different purposes of cyclist journeys.

Figure 5.19:. Visualization of casual cyclists' routes.

A second map zooms into a central urban area, showing in detail the diverse level of cyclist flow through the different streets. The third map illustrates bike messenger mobility at the same metropolitan scale and extent used in the first map, so that it not only represents the general cyclist flow but makes possible the comparison between the two different mobilities. In this case, routes are symbolized according to the bike messengers company. The map revealed some differences, such as the extent of the global cycle track, but also others that became clearer in the fourth map that zooms into another central urban area. The visualization of the tracks evidenced a stronger preference for riding in the main streets even where they have the highest motor traffic flow.

Figure 5.20: Visualization of casual cyclists' routes.

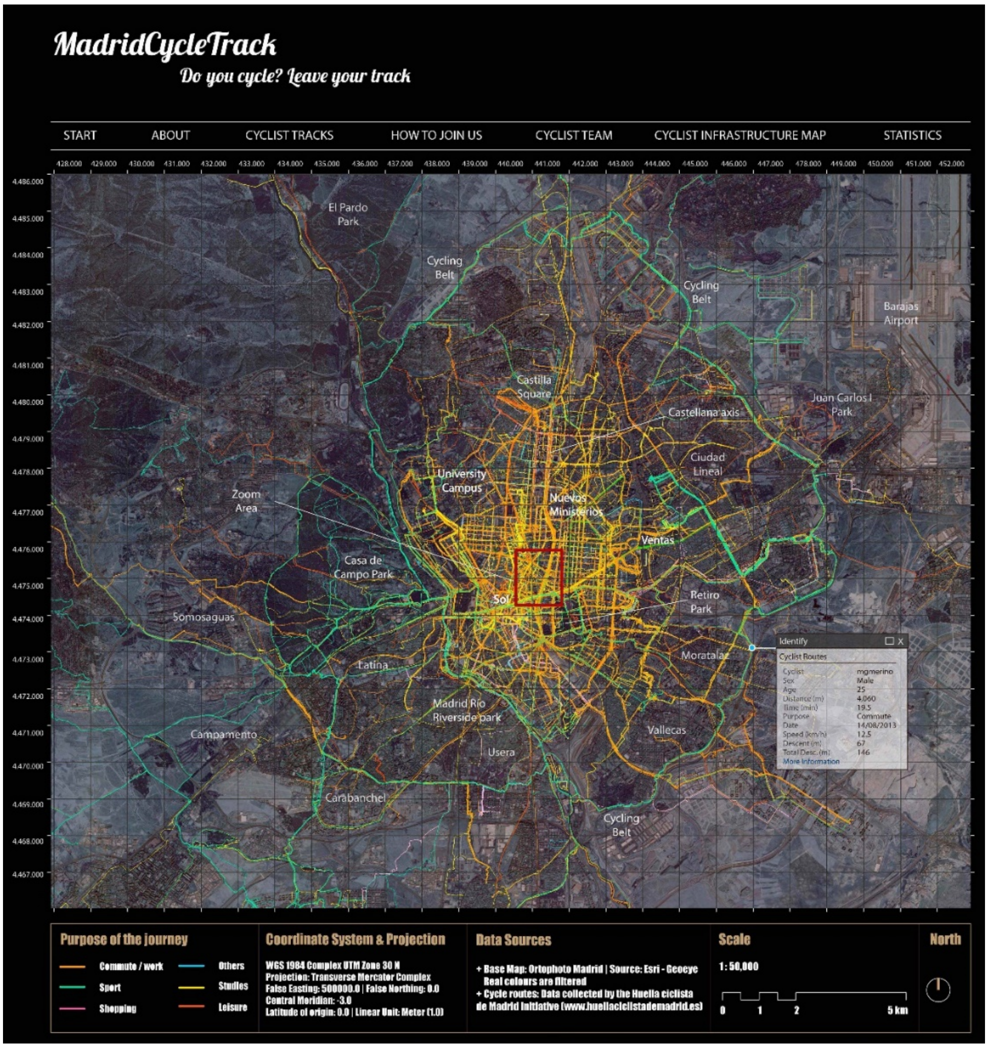
The maps represent the routes collected from the GPS tracks and the routes designed by cyclist through the "Design your route" online map. In order to represent cyclist flow as a collection of different routes, these track lines were deliberately not matched to any street network layer (Figure 5.19).

Finally, the routes are displayed over a satellite image, a GeoEye ortophoto obtained by using an ESRI web map service with ArcGIS 10.2. Different Photoshop filters were applied to the orthophoto to make it more homogeneous, to reduce contrast without losing the detail an ortophoto brings compared to base maps, and increasing the contrast of the displayed routes, allowing an accurate but a clear visual exploration of the map at the same time. Administrative or political boundaries (in the case of Madrid not at all related to extent of the urban area) were intentionally avoided in order to highlight the natural, irregular and progressively diffuse boundaries of the cycle track.

5.4.1 Casual cyclists' map

Description of the map, from the original map canvas: These maps illustrate the cycle routes collected through the initiative Huella Ciclista de Madrid (Madrid Cycle Track). The initiative was launched through an online platform (website available at www.huellaciclistademadrid.es). In this platform, different online maps represented the evolution the collective track over time. The Casual Cyclist map is represented here as embeded in the existing online platform.

Figure 5.21: Casual Cyclists' track

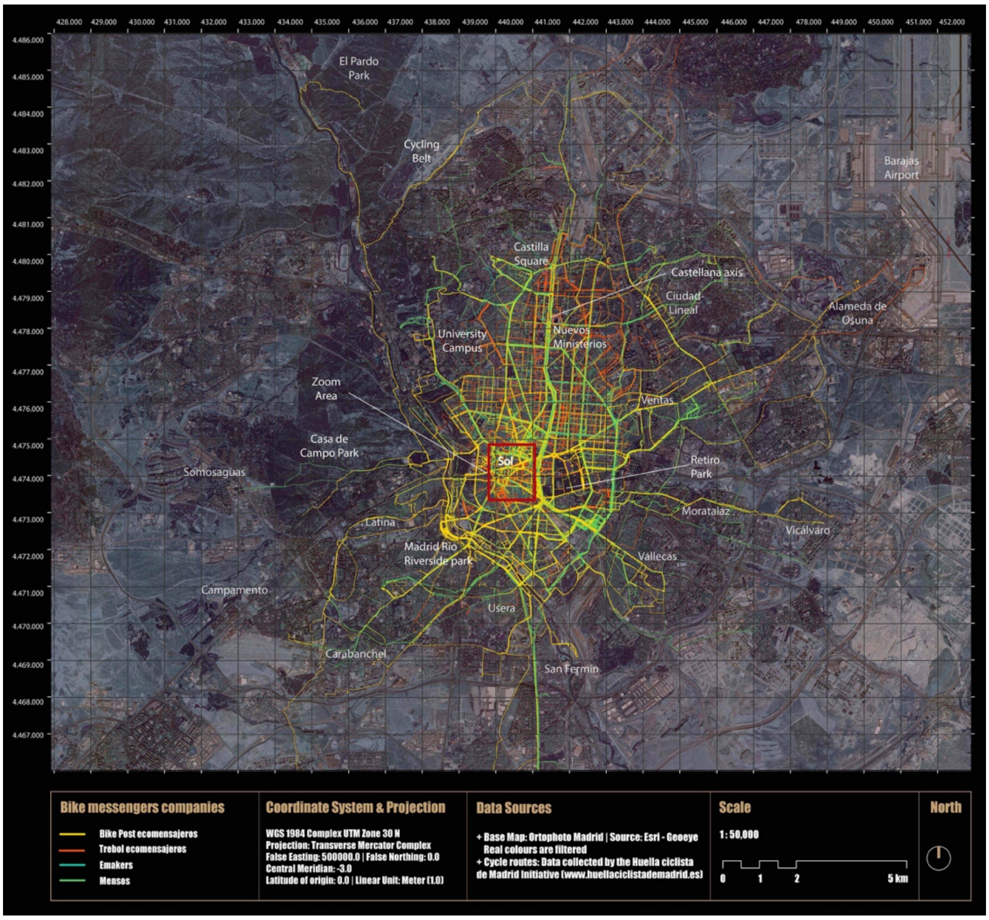


The pop up window represents the information obtained for each track. The total number of cycle routes gathered was 6,022 resulting in 48,122 km of GPS tracks uploaded by 328 volunteers participating from June 2013 to September 2014, taking into account both the casual cyclists and bike messengers. Casual cyclists' routes were mainly collected from June 2013 to March 2014.

5.4.2 Bike messengers' map

Description of the map, from the original map canvas: The bike messengers' routes were collected from November 2013 to September 2014. A total number of 2,052 routes were originally gathered from four different companies, providing 10,777 cycled kilometers.

Figure 5.22: Bike messengers' track



5.5 Dynamic visualization

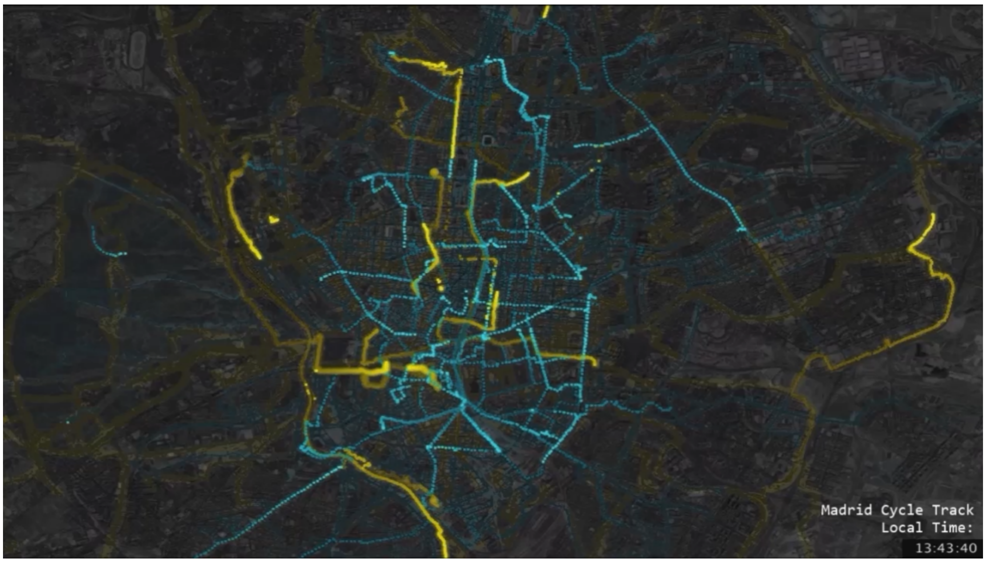
The online visualisation animates the activity of both casual users and bike messengers, shown according to time of day, but collapsed from multiple days (including several journeys by some users) onto one day, to illustrate routes and activity as they vary by time of day. In doing this, we have combined journeys from weekdays and weekends, special events and bank holidays, and journeys taking place in different days and weeks – all of which might have different characters due to different reasons for journeys, weather, seasons and traffic.

The visualisation was produced using the Processing programming language (http://processing.org) using code written for the purpose (https://github.com/martinaustwick/GPS-vis). The journey data is stored in a mysql database in two separate tables (one each for couriers and casual users); each table contains a series of rows which has a user ID, location and timestamp associated with that location.

In each frame, a query is sent to the couriers table, requesting all data points which were recorded less than 20 seconds after the current timestamp. These points are drawn on the screen with a two increasingly large and transparent ellipses (8 and 16 pixels) drawn at the same location. This is a simple method to produce a "heatmap" effect when multiple data points exist in close proximity at the same or similar timestamps, or when the same locations were recorded at the same time on consecutive days. This process is then repeated for the casual users, but the colour is changed to distinguish these two groups.

In between frames, a partially transparent version of the underlying map is redrawn, meaning that the location of points in previous timestamps remains partially visible, creating the illusion of a continuous path. By decreasing transparency (increasing alpha value), those previous values become more strongly obscured, emphasising the "current" position of cyclists; by increasing transparency (reducing alpha), prior paths are more obvious, at the expense of the most current data. Each frame, a .jpg image is captured, creating some 3,150 images (17.5 hours at 3 images per minute) which when assembled at 30 frames/second results in a movie of under two minutes.

Figure 5.23: Screenshot of the visualization (Link to web).



5.6 Conclusions

The maps presented in this paper visualise the distribution of cyclist flow for the first time in the study area. This visualization reveals mobility patterns regarding the use of bikes for different purposes and disaggregated by different socio-demographic characteristics, allowing us to understand better bike mobility trends and cyclist behaviour. But the maps have played a crucial role behind the visual exploration and the analysis of the outputs. The creation of online maps was central in the design of the initiative. Online maps were dynamic, they represented the evolution of the collective track over time and let volunteers to visualise their contribution. Furthermore, cyclists were also able to design their routes on the map, so that they became not only a representation tool but an instrument for capturing new data and engaging our community of cyclists. Maps play a central role in innovative participatory projects that bring new possibilities for collecting new data and allowing communities affected by planning changes to directly contribute to those processes. *Madrid Cycle Tracks* has demonstrated new ways to engage community stakeholders as active citizen scientists in helping to shape their city infrastructure, and demonstrated the value of interactive mapmaking and visualisation in building and maintaining these communities.

MadridCycleTrack

Visualizing the cyclable city

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Martin Zaltz Austick [2] | Centre for Advance Spatial Analysis (CASA) | University College of London

Casual Cyclists

These maps illustrate the cycle routes collected through the initiative Huella Ciclista de Madrid (Madrid Cycle Track). The initiative was launched through an online platform (website available at www.huellaciclistademadrid.es). In this platform, different online maps represented the evolution the collective track over time. The Casual Cyclist map is represented here as embeded in the existing online platform. The pop up window represents the information obtained for each track.

The total number of cycle routes gathered was 6,022 resulting in 48,122 km of GPS tracks uploaded by 328 volunteers participating from June 2013 to September 2014, taking into account both the casual cyclists and bike messengers. Casual cyclists' routes were mainly collected from June 2013 to March 2014.

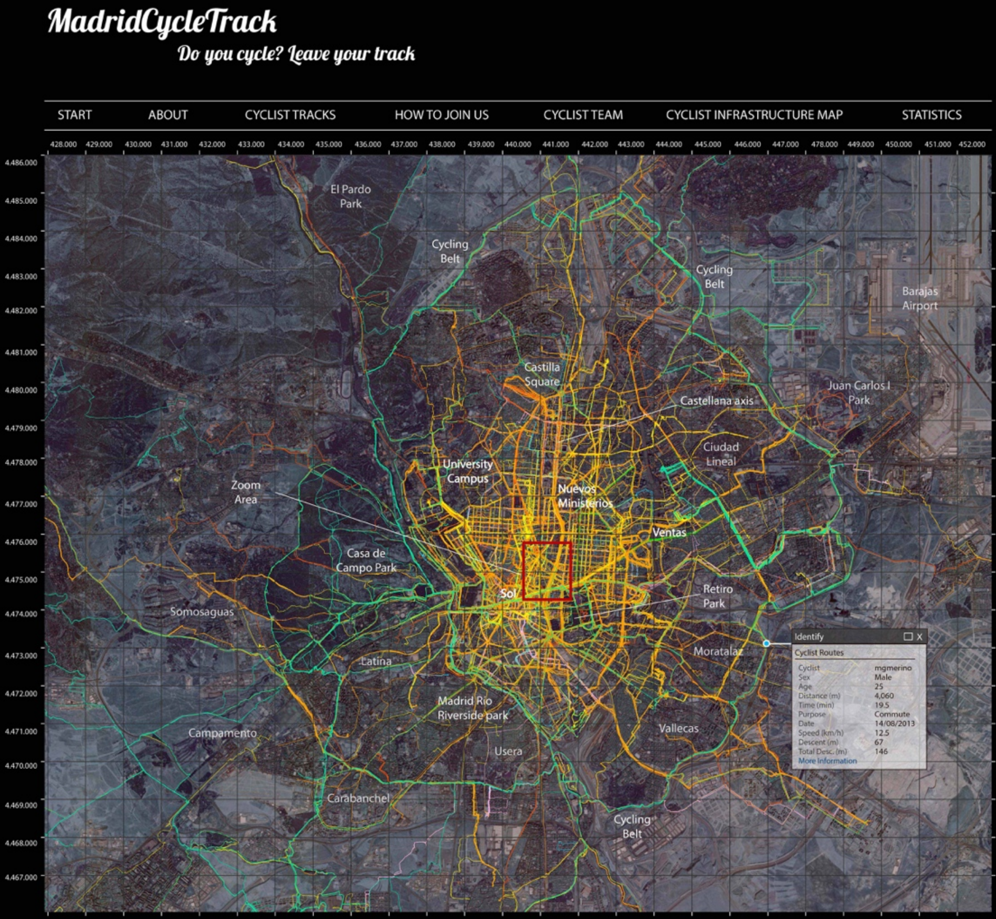
Table 1. Route statistics according to the purpose of the journey | (* Routes with known purpose)

Purpose of the journey	Routes (%)	Routes* (%)	Speed Average (Km/h)	Time Average (minutes)	Distance Average (metres)
Commuting	31.11	42.19	15.82	24.52	5,889
Leisure	17.17	23.28	15.15	23.94	5,705
Sport	5.72	7.76	16.19	80.81	21,002
Shopping	6.30	8.55	14.66	22.29	5,648
Management / other	5.51	7.47	15,18	17.07	4,231
Study	7.93	10.76	14.82	21.12	5,201
Unknown	26.26	-	14.28	28.30	6,638
Total / Average	100.00	100.00	15.42	31.64	7,947

Coordinate System & Projection
WGS 1984 Complex UTM Zone 30 N
Projection: Transverse Mercator Complex
False Easting: 500000.0 | False Northing: 0.0
Central Meridian: -3.0
Latitude of origin: 0.0 | Linear Unit: Meter (1.0)

Scale
1 : 5,000
0 100 200 500 m

North



Purpose of the journey
Commute / work
Sport
Shopping
Others
Studies
Leisure

Coordinate System & Projection
WGS 1984 Complex UTM Zone 30 N
Projection: Transverse Mercator Complex
False Easting: 500000.0 | False Northing: 0.0
Central Meridian: -3.0
Latitude of origin: 0.0 | Linear Unit: Meter (1.0)

Data Sources
+ Base Map: Ortophoto Madrid | Source: Esri - Geeoye
Real colours are filtered
+ Cycle routes: Data collected by the Huella ciclista de Madrid Initiative (www.huellaciclistademadrid.es)

Scale
1 : 50,000
0 1 2 5 km

North

Bike messengers

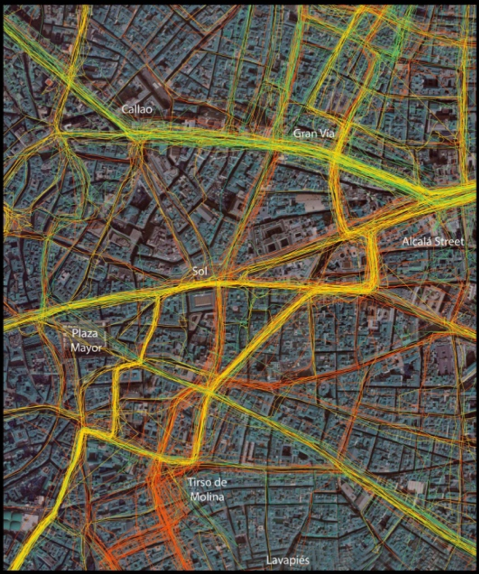
The bike messengers' routes were collected from November 2013 to September 2014. A total number of 2,052 routes were finally gathered from four different companies, providing 10,777 cycled kilometres.

Table 2. Route statistics according to the type of bike of the messengers

Type of bike	Routes (uds.)	Speed Av. (km/h)	Distance Av. (m)
Normal Bike	1,553	19.6	5,245
Bullit bike (elect.)	131	19.7	3,061
Cargo trike (elect.)	37	11.4	2,494

Table 3. Routes by company

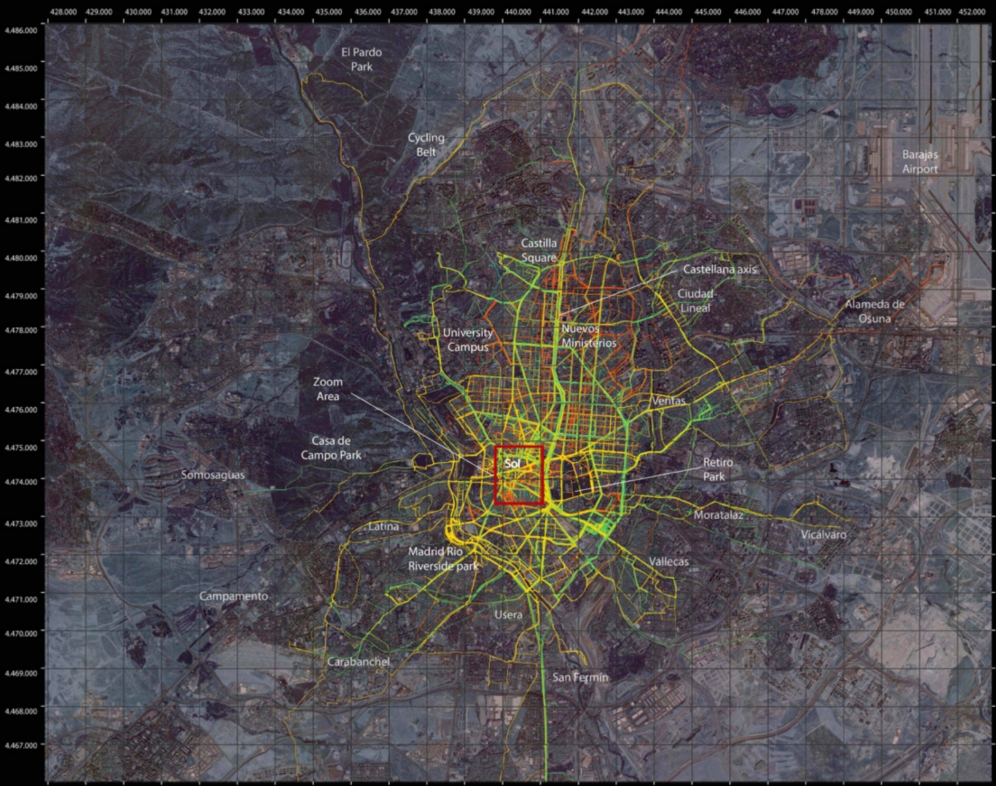
Company	Routes (uds.)
Bike Post	400
Trébol	852
Emakers	389
Mensos	411



Coordinate System & Projection
WGS 1984 Complex UTM Zone 30 N
Projection: Transverse Mercator Complex
False Easting: 500000.0 | False Northing: 0.0
Central Meridian: -3.0
Latitude of origin: 0.0 | Linear Unit: Meter (1.0)

Scale
1 : 5,000
0 100 200 500 m

North



Bike messengers companies
Bike Post ecomensajeros
Trebol ecomensajeros
Emakers
Mensos

Coordinate System & Projection
WGS 1984 Complex UTM Zone 30 N
Projection: Transverse Mercator Complex
False Easting: 500000.0 | False Northing: 0.0
Central Meridian: -3.0
Latitude of origin: 0.0 | Linear Unit: Meter (1.0)

Data Sources
+ Base Map: Ortophoto Madrid | Source: Esri - Geeoye
Real colours are filtered
+ Cycle routes: Data collected by the Huella ciclista de Madrid Initiative (www.huellaciclistademadrid.es)

Scale
1 : 50,000
0 1 2 5 km

North

6 Cyclists do better. Analysing urban cycling operating speeds and accessibility

Remarks

This section is based on the research synthesized in the paper titled "*Cyclists do better. Analyzing urban cycling operating speeds and accessibility*", submitted to the *International Journal of Sustainable Transportation* in October 2017, accepted, and currently under review.

6.1 Introduction and background

In the context of a growing interest in promoting a more sustainable urban transport, many researchers have analysed cyclist's behaviour in order to obtain the understanding necessary to foster effective policies and build useful cycle infrastructures. With different purposes, these analysis had traditionally been based on household or specific group surveys carried out through Stated Preference techniques (Kroes & Sheldon, 1988; Ortúzar et al., 2000), Revealed Preference methods that, for instance, asked cyclists to design their routes on a map (Ben-aiuva & Morikawa, 1990), or mixed techniques that combined both methodologies (Yang & Mesbah, 2013). However, over the last ten years, the emergence of new location devices and the consequent availability of geolocated data have led to a growing number of studies (Romanillos et al., 2016) that have shed light on different aspects of cycling mobility that were underexplored.

Especially significant was the research based on the analysis of Global Positioning System (GPS) data collected through different initiatives and, more recently, the studies based on the thousands of GPS routes collected by some app companies widely used by cyclists, Strava perhaps being the most remarkable one. However, although the volume of data that these companies make available surpasses the data collected by any of the previous research initiatives by far, the data have an important limitation: in order to preserve the anonymity of users, the data are always aggregated, so the single GPS tracks are not available and there is not even any associated information about cyclists (such as age or gender) or the trip (such as the purpose of the journey). The impact of these factors was exceptionally studied by some research initiatives (J. G. Hudson et al., 2012) focusing on the analysis of their own data samples, yet in any case, they rely on the analysis of the data aggregated by route. Furthermore, most of these studies are essentially focussed on the development of route-choice models (Romanillos et al., 2016) rather than on a detailed study of cycling patterns according to socio-demographic profiles or to different characteristics of the network. Thus, there are some important cycling aspects or dynamics that have not been properly explored.

One of the important cycling dynamics that remains underexplored is the estimation of cycling operating speed according to different local factors (slope, traffic, types of roads or bike lane, etc.), the different characteristics of cyclists (gender and age) or other variables, such as the purpose of the journey. The analysis of cyclists' operating speeds according to these (and other) factors is essential for the study of key aspects of cycling mobility, such as the estimation of travel times — already studied by Salonen & Toivonen (2013) — and the potentially derived accessibility analyses, the study of cycling competitiveness in relation to other transport modes — already explored by Ellison & Greaves (2011); Börjesson & Eliasson (2012) and Witlox & Tindermans (2004) — and for the correct development and calibration of cycling route-choice models, as well as for the evaluation of cycling risks and the planning and design of bike infrastructures and policies.

However, with some exceptions mostly focussed on Chinese case studies, cycling speeds have yet to be studied in detail. Liu, Shen and Ren (1993) analysed cyclists' free-flow speed in Beijing and reported an average of 14kph. (Wei, Huang, & Wang, 1997) studied the different free-flow speeds on regular roads and in segregated bike lanes, resulting in 13.9kph and 18.2, respectively. Cherry (2007) conducted an exhaustive research on electric bike mobility in Chinese cities, reporting a free-flow speed of 18.2kph, significantly higher than the 13.0khp that corresponded to classic bikes. Just one year later, Lin, He, Tan, & He (2008) went one step further and analysed the operating speeds of 552 e-bicycle riders and 232 bicycle riders in the city of Kunming, China, according to age and gender. Though their results were interesting and evidenced different speeds, the followed methodology presented some remarkable limitations. The study was only conducted on bicycle-exclusive lanes and in straight and flat-road sections. The selected road was then video-recorded and the operating speed was measured by manually registering the time that it took cyclists to ride a measured distance. Apart from this, cyclists were classified into three different age groups (under 25, 25-50 and over 50 years old), based on the researcher's decision. Similar methodologies of vision-based analysis of cyclists' speed, relatively improved by automated video analysis techniques, have been applied (Kassim, Pascoe, Ismail, El Halim, & El Halim, 2012), but with a limited sample in terms of locations.

More recently, similar results have been found in Hangzhou, China, by (Jin et al., 2015) when estimating cycleway capacities, and by Xu et al. (2015), who developed several models with the similar aim of predicting cycling flow speed according to the cycleway width, the type of bike and different characteristics of cyclists (age and gender).

Finally, other studies have also analysed cyclists' crossing speeds at signalized intersections and traffic lights (Guo, Liu, Bai, Xu, & Chen, 2014), a fundamental measure when evaluating crash risk and its severity, which has also been highlighted and studied by Vlakveld et al. (2014) and Xu et al. (2015). In summary, as far as we know, cycling speeds have not been studied considering a wide range of factors at the same time, so the knowledge that we have about it is always narrowed to a very limited sample and the influence of specific and local aspects.

This research pursues two main goals: the first one is to perform a detailed analysis of cyclists' operating speeds according to a wide range of factors, and the second one is to conduct a comparative analysis of accessibility, evaluating competitiveness between different transport modes: cycling (including BiciMAD-Madrid Bike Share System-), walking, private car and public transport.

With this aim, initially, in relation to the first goal, we have studied the thousands of trips collected through the *Madrid Cycle Track* research initiative (Romanillos & Zaltz Austwick, 2015) by exploring their correspondent GPS dataset at a track-point level. Cyclists' operating speed can be then analysed according to important local factors that affect cyclists along the different sections of their journey, such as the slope, the type of road, the existence –and type- of bike infrastructures, the motor traffic speed or the distance to a signalized intersection or a non-signalized one. Since the initiative collected volunteers' information as well, cyclists' speed is also analysed according to age and gender, in addition to the purpose of the journey.

The research includes the analysis of regular cyclists' trips, as well as the analysis of the bike messengers' routes collected from four different companies through the same initiative. Following a similar methodology, their different operating speeds are analysed according to the different types of bikes (regular, cargo, e-cargo bikes and e-tricycles), and then compared to the results obtained for regular cyclists. By conducting diverse OLS regression models to analyse cyclists' speed considering all these factors, we are able to estimate cyclists' travel times for the whole street network (and not only in the street-network arcs where we have cyclists' records) and, furthermore, we can also predict cyclists' travel times and accessibility in future scenarios.

The analysis is not extended to Madrid Public Bike-Share System (BiciMAD), since the dataset provided by the Municipal Transport Company (EMT) was basically a collection of GPS track points, recorded with an average interval of 75 seconds. This temporal resolution is much lower than the one typically obtained with commercial smartphone apps or GPS devices, such as the one obtained in through the Huella Ciclista de Madrid Initiative, which tends to be around 2 seconds. For this reason, the data is not valid for the kind of analysis carried out here, based on the detailed analysis of speeds at every road network segment.

Finally, regarding the second goal, we have calculated a series of isochrones from a central point in Madrid, according to the estimated casual cyclists' speed, BiciMAD users' average speed, an average walking speed, private car speeds in Madrid (considering a high-resolution network and accurate traffic speeds obtained from the *TomTom*® database) and public transport travel times according to the General Transit Feed Specification (GTFS) data obtained from the Regional Transport Consortium of Madrid. Different maps illustrate the diverse isochrones and a table summarizes the area covered by each transport mode, revealing that cycling is the most competitive one for trips under 20 minutes.

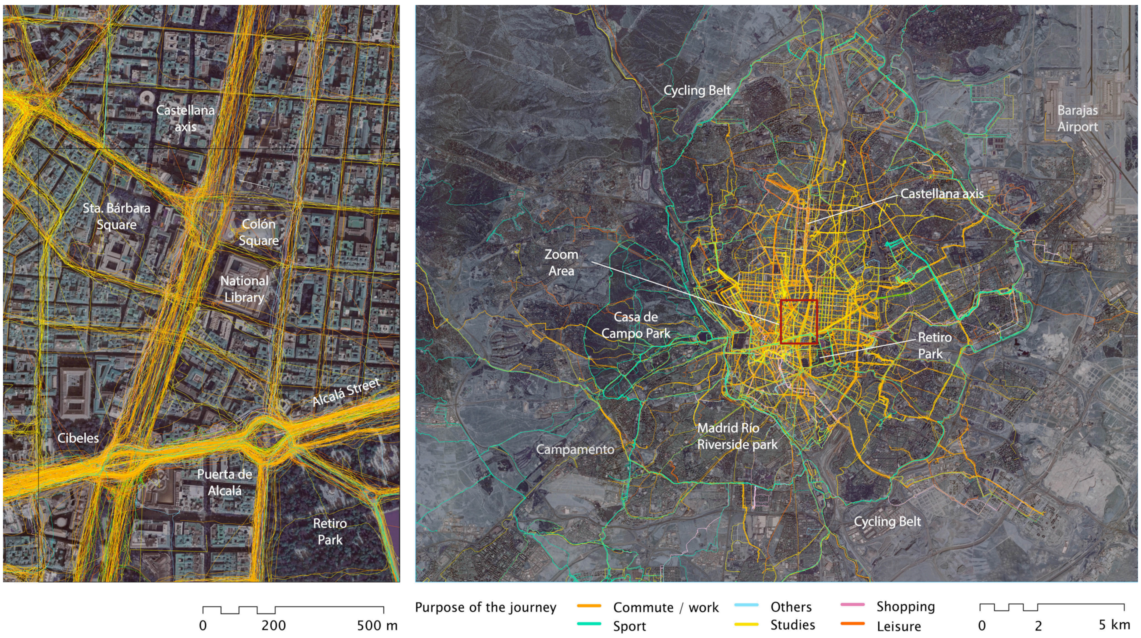
The chapter is structured as follows: after this introduction, Section 2 and 3 describe the data and the methodology, respectively, Section 4 shows the main results, and Section 5 presents the conclusions and final remarks.

6.2 Data

6.2.1 Cyclists' data collection: The Madrid Cycle Track initiative

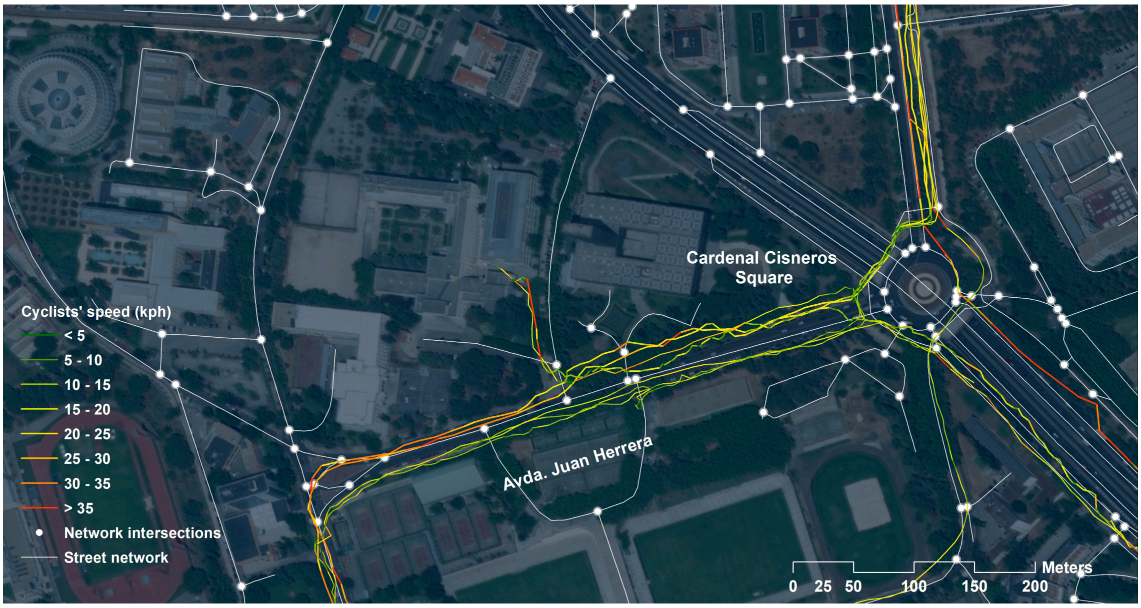
This research is based on the analysis of the cyclists' trips collected through the *Madrid Cycle Track* initiative (www.huellaciclistademadrid.es). Since the data gathered have already been described in detail by Romanillos & Zaltz Austwick (2015), we will only introduce the basic figures here. The initiative collected 6,022 cycle routes uploaded by 328 volunteers, taking into account casual cyclists and bike-messengers, resulting in 48,122 km of cycling tracks (Figure 6.1). Over three hundred cyclists contributed with 37,345 km of cycle routes obtained from 3,970 journeys. Regarding the purpose of the journey, 42.19 % of the routes corresponds to commuting, 23.28% to leisure, 10.76% to study, 8.55% to shopping, 7.76% to sport and 7.47% to errands. In terms of gender, the proportion of males and females in this sample was 72%-28%, respectively (figures that correspond well to existing local surveys (DOYMO, 2011; Monzon de Cáceres et al., 2011). This study does not include routes travelled with e-bikes, since the sample obtained was very poor. In addition, four different bike messenger companies participated in the initiative, providing 2,052 routes and 10,777 cycled kilometres. The total number of cyclists participating in the initiative was 23.

Figure 6.1: GPS routes collected through the Madrid Cycle Track initiative.



While the paper published by Romanillos & Zaltz Austwick (2015) focussed on visualising the global cycle track of the city of Madrid, this study explores the GPS dataset collected at a track-point level. The GPS app registered cyclists' location every two seconds, providing records on latitude, longitude and local time. By generating the GPS track-lines from the points, it was possible to calculate cyclists' speed every two seconds. Before going into the process of GPS data cleaning (described later in the Data pre-processing sub-section), the simple visualization of these GPS track lines according to cyclists' speed (Figure 6.2) evidences the impact that different factors have on it. For instance, the figure illustrates several cyclists' tracks along a steep street (Avda. Juan Herrera), showing the speed asymmetry between those going up (from left to right) and those going down (from right to left), as well as the impact of street junctions, where cyclists' speeds are significantly reduced. The goal of this study is to explore, at the level of spatial accuracy that GPS records bring, the impact of these and other factors. In this sense, the Madrid Cycle Track initiative collected information about other variables that have a potential impact on cycling speeds, such as age and gender (regarding cyclists) or the purpose of the journey (regarding routes).

Figure 6.2. GPS track lines represented according to cycling speed.



6.2.2 Other data sources

In order to improve the analysis by including other variables that potentially affects cyclists' operating speeds, the routes collected were fed with data from different sources. All the datasets were integrated in a Geographic Information Systems (GIS) environment.

First, the GPS track lines were map-matched to a detailed street network based on the March 2013 version of *TomTom®* for the Spanish road network. The *TomTom®* network is actually the most accurate street network found in Madrid, contemplating not only roads but also pedestrian streets and bike infrastructure, and includes over 160,000 street-segments for the metropolitan area of Madrid that cover the collected cycling routes. In addition, TomTom® databases provided relevant information, such as the direction of traffic, or information on variables that could influence cyclists' operating speed, such as the maximum motor traffic speed or the real average traffic speed per road segment and according to different time frames (average real speed on weekdays, during the weekend, on weekdays during rush hour, etc.).

After this, the *TomTom®* street network was edited and completed with relevant information obtained from other local data sources. Slopes were calculated for each street segment by calculating the elevation for each node of the street segments from a high resolution Digital Elevation Model (cell size = 5 meters) obtained from the National Geographic Institute of Spain (http://www.ign.es). Although the *TomTom®* street network was supposed to contemplate the existing bike infrastructure, it was not complete. Because of this, the network was edited and the bike infrastructure updated, including all the eight different kinds of bike infrastructure considered in the Madrid Cycling Master Plan, listed in Section 3.2.1. This information was downloaded from the Madrid Open Data Portal (http://datos.madrid.es), where we were also able to obtain the geolocated datasets of the existing traffic lights. When comparing accessibility between different transport modes, we considered the *TomTom®* speed profiles (every 5 minutes) in order to estimate the average speed at 8h.

Finally, in order to perform analysis of cycling competitiveness in relation to other transport modes, public transport (bus, train, tram and underground) travel times according to the General Transit Feed Specification (GTFS) data were obtained from the Regional Transport Consortium of Madrid. This data also provides travel times for every hour over the course of the day.

6.3 Methodology

6.3.1 Data preprocessing

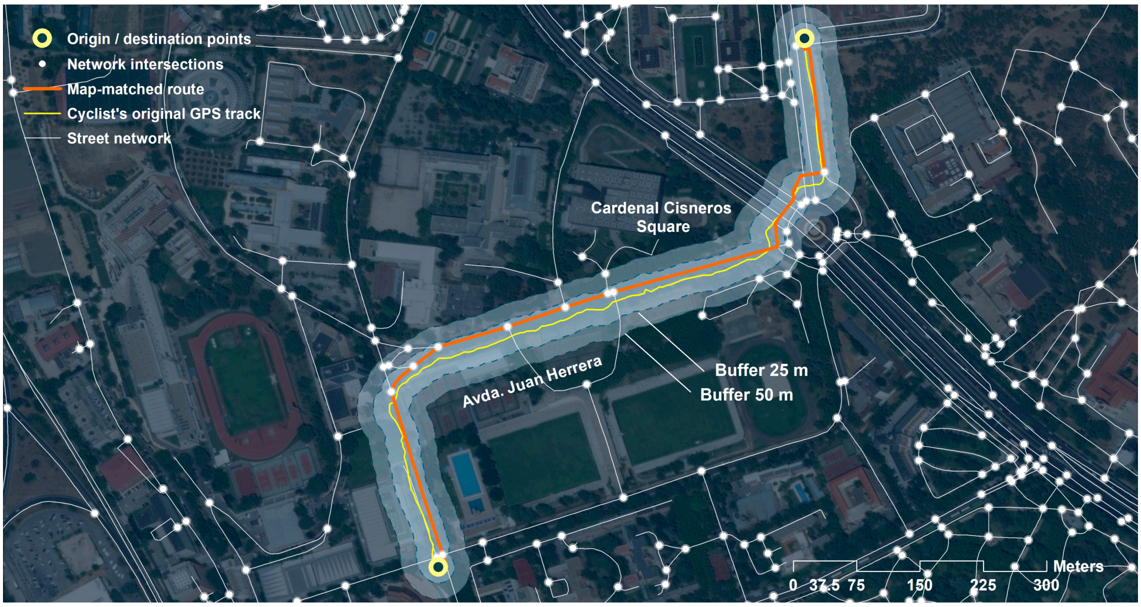
6.3.1.1 Map matching process

The Madrid Cycle Track initiative collected the cyclists' routes through two different applications (*Map My Tracks* and *Garmin Connect*), which recorded cyclists' location every two seconds in GPX —or GPS exchange— format, providing records on latitude, longitude and local time. The GPX files were downloaded from the app and imported into a GIS environment, where we obtained the GPS track-points and eventually generated the GPS track-lines from them. In order to analyse cyclists' routes according to the different variables that we were considering, the GPS track-line obtained must be matched to our street network. This is commonly known as the map-matching process, and it has been tackled by researchers following different procedures (Schuessler & Axhausen, 2009a). For this study, based on the map-matching algorithm created by Dalumpines & Scott (2011), we developed a new version that improves an aspect that was relevant for the purpose of our research.

The commonly known map-matching process has been tackled by researchers following different procedures, described and classified by Schuessler & Axhausen (2009), who also implemented the advanced map-matching algorithm used by Hood et al. (2011) when analysing the cycle tracks collected in San Francisco. The results obtained revealed the complexity of the problem: only 1,454 out of the 2,282 original traces were matched to the network, and still some of them could contain the significant errors common to the map-matching geometric procedures, that even led to some researchers to check each route and manually correct the errors (Snizek, Sick Nielsen, & Skov-Petersen, 2013). Much better map-matching results are obtained when combining geometric and topological procedures, since they “consider the connectivity of the network in assessing the feasibility of a route” (J. G. Hudson et al., 2012). Between these hybrid approaches, the algorithm developed by (Dalumpines & Scott, 2011) was especially interesting for our research, because of its easy integration into a GIS environment (using ArcGIS’s Network Analyst tools) and because of the results obtained by (K. A. Larsen, Meyer, Duthie, & Khan, 2013) in the map-matching process applied to the routes collected in Texas, with 88% success.

For this study, based on the map-matching algorithm created by Dalumpines & Scott (2011), we developed a new version that improves an aspect relevant to the purpose of our research. The procedure basically creates a buffer around the GPS track-line that constrains the estimation of the shortest path between the origin and the destination, by using Dijkstra’s algorithm (see Figure 6.3). In this process, the definition of the buffer distances determines the results: a buffer too small may prevent the matching of many routes, while a buffer too wide may lead to inaccurate or incorrect routes. After a sensibility analysis, Dalumpines and Scott concluded that with buffer distances below 25 m, the shortest-path algorithm did not find any routes, and with buffer distances above 60 m, inaccurate routes were the result.

Figure 6.3. Illustration of the Map-matching process. Route map-matched within the 25 m distance buffer.



Our improvement in this sense was to develop a model that did not fix a specific buffer distance, but rather a dynamic buffer that ranges from a lower and an upper limit that we established from 25 to 250 m. The algorithm starts by attempting to find the route within the buffer that corresponds to the minimum distance and, if it does not succeed, the process is repeated by incrementing the buffer distance by 25 m, till the route is eventually matched. Each route will have a field that informs on the buffer distance at which it was generated, so that we can obtain an idea of how accurate the matched route is. This way, the output routes are as accurate as possible and, in our case, we could map-match almost all the GPS tracks (96%). Of course, some of them are matched with buffer distances over 60 and even 100 m, which certainly could be considered unacceptable, but here comes the following appreciation that we considered relevant. There are GPS routes that are quite accurate and merely contain exceptional errors in some specific segments (probably due to a temporally poor GPS signal). As a result, these routes often cannot be matched considering low buffer distance. However, for the purpose of this study, we did not need entire matched routes, but rather accurate map-matched route segments. Our algorithm allowed us to select a larger amount of route arcs perfectly matched out of routes that otherwise could have been discarded, since it informs on the distance between the original GPS track and the route for all the route segments.

6.3.1.2 Selection of route segments

In addition to the buffer distance value, we considered other criteria in order to establish what could be considered a quality control for the analysis of cycling speeds in each of the route arcs: general matched route buffer distance in map-matching process < 150 m, maximum track lines distance to map-matched route (could be considered a relative buffer distance, measuring the actual accuracy of the segment) < 10 m, average speed < 60 kph (segments with higher speed were mainly errors). In addition, we considered four criteria that basically select the route segments that are long enough to avoid errors when estimating speed (since the GPS collects points every 2 seconds, the speed estimated in a very short segment —5 seconds— could be easily over-or underestimated, if we considered 4 seconds or 6 seconds respectively): minimum network arc length > 20 meters, minimum time duration of track line ≥ 8 seconds, minimum number of track-points attached ≥ 4 and a ratio between the map-matched route arc length and the one of the original GPS track-line ranging from 0.75 to 1.25.

As result of this filter, the sample obtained for the analysis, including both casual cyclists and bike messengers' routes, consisted of 227,284 out of the 361,610 total route arcs (62.8%). In terms of the street network considered for the analysis (and taking into account that some of this route arcs are overlapped, that is to say, are different records on the same street arc), the number of street-network arcs with route information was 35,464 out of the 117,858 total arcs (30.0%).

6.3.2 Estimation of operational speeds through Ordinary Least Squares regressions

The Ordinary Least Square (OLS) regression is one of the most common techniques when exploring the relationships between a certain variable that we want to explain —the dependent variable— and the variables we believe influence this dependent variable —the explanatory variables —, when the relationship between them is linear. We have used this technique because it allows to estimate the sign and the specific weight (coefficient values) for each explanatory variable. In consequence, we can compare the impact of the different variables as well as we can create models which will be able to estimate the average speed (dependent variable) that would correspond to a potential future scenario, determined by the different coefficients to be considered for that possible scenario. In this section, we identify the factors that may influence cyclists' speed, we select the explanatory variables accordingly, and we define the different OLS regressions to perform. Different exploratory regressions were performed (by using the *ArcGIS-Spatial Statistics Exploratory Regression* tool) in order to verify the linearity of the relationship between the dependent and the explanatory variables, as well as their potential redundancy, statistical significance, bias and performance. The results tables of the following sections show the variables eventually introduced in the final models (for instance, *Total trip time* and *Total trip distance* were redundant, and only the first one was eventually introduced in the models).

6.3.2.1 Identification of factors affecting cyclists' speed and selection of explanatory variables

Cyclists' operating speed may be affected and determined by a wide range of factors. Different studies have analysed the impact of some of them, such as slope (Monzón de Cáceres et al., 2008), the existence of segregated bike lines (Wei et al., 1997), the effect of electric assistance in the case of e-bikes Cherry (2007), the influence of age and gender Lin, He, Tan, & He (2008), the impact of signalized intersections and red lights (Guo et al., 2014) or even the weather (Helbich, Böcker, & Dijst, 2014). However, as we observed in the introduction section, most of these studies presented some limitations, in terms of either the methodology followed or the sample on which the analysis is based. In addition, some important factors are missing and, in any case, the study of a wide range of factors simultaneously had not yet been carried out. The information collected through the Madrid Cycle Track initiative provided a good opportunity to conduct a more complete analysis including the factors listed on Table 6.1 as possible explanatory variables. For the different analyses conducted, routes without information on any of these variables were not included.

Table 6.1: List of possible explanatory variables, description and expected sign

Explanatory Variable		Description	Expected sign
1.	Slope	Slope in percent rise, estimated by calculating the elevation for each node of the GPS route segments from a high resolution Digital Elevation Model (cell size = 5 meters).	Negative
2.	Intersections / km	Calculated as the ratio of number of intersections per route segment (km).	Negative
3.	Traffic lights / km	Considered as the ratio of number of traffic lights per route segment (km).	Negative
4.	Age	Age reported by the volunteers (all of them over 18 years old).	Negative
5.	Female	Gender, reported by the volunteers, introduced as a dummy, considering male by default (because around ¾ of the sample are males)	Negative. Males are expected to cycle faster.
6.	Purpose of the journey	Classified as commuting, sport, leisure, study, shopping and errands.	Diverse signs according to categories.

7.	Type of road regarding bike infrastructure	According to the Madrid Cycling Master Plan classification: Bike lane on the sidewalk, segregated bike lane on the sidewalk, non-segregated bike lane, segregated bike lane in parks/countryside with adapted surface, segregated bike lane in parks/countryside without adapted surface, segregated bike lane in parks or in the countryside with a slightly adapted surface, lane shared with cars (no infrastructure) and "lane with cycling preference and speed reduction".	Diverse signs according to categories.
8.	Total trip time (min)	Total trip time in minutes, obtained from the GPS records.	Negative
9.	Total trip distance (m)	Total trip distance in meters, calculated from the map-matched route length, not from the GPS track-lines, which may lead to under-or overestimations depending on the amount of noise in the GPS point records.	Negative
10.	Net increase in altitude (m)	Net increase in altitude (meters), obtained from the map-matched route difference in origin and destination elevation data.	Negative
11.	Net increase in altitude (m)	Accumulated increase in altitude (meters), calculated from the map-matched route accumulated difference in the route segments elevation.	Negative
12.	Maximum traffic speed (kph)	Maximum traffic speed (kilometres per hour) per street segment, according to TomTom® database.	Positive
13.	Real average traffic speed (kph)	Real average traffic speed (kilometres per hour) per street segment, for the weekdays-mornings time frame according to TomTom® database.	Positive
14.	Type of bike	Only in the case of bike messengers' routes, classified as normal bicycle, cargo bicycle and cargo tricycle	Diverse signs according to categories.
15.	Weather	As in the case of bike messengers' routes (provided by the Garmin Connect platform linked to the messengers' GPS devices), reported as sunny, cloudy or rainy	Negative for cloudy and rainy values.

6.3.2.2 Definition of the different OLS regressions to perform

We have defined three different OLS regression models with diverse purposes or applications. In all of them, the categorical values of some variables (gender, purpose of the journey, type of road in terms of bike infrastructure and type of bike and weather) have been introduced as dummies.

The first OLS regression model estimates an average cycling speed for each street-network segment according to its properties or conditions, and is useful for creating general cycling isochrones or accessibility analyses. It considers the following 6 explanatory variables: slope, intersections, traffic lights, type of road according to bike infrastructure, maximum traffic speed and real average traffic speed.

The second model assigns an average cycling speed to each route segment according to the street-network and other properties related to the trip or the cyclist and, considering more information, provides a more accurate speed estimation, which is useful for router apps when estimating travel times. The model is based on the analysis of 13 explanatory variables, the ones introduced in the previous model, as well as age, gender, purpose of the journey, total trip time, total trip distance, net increase altitude, accumulated increase altitude, maximum traffic speed and average traffic speed.

Finally, the third model focuses on bike messengers' routes, and estimates an average cycling speed to each route segment according to the street-network and other properties related to the trip, the conditions (weather) or the type of bicycle. As with the previous model, this one provides for more accurate travel times based on more specific information. The model is based on the analysis of 12 explanatory variables, the ones introduced in the first model, as well as type of bicycle, weather conditions and —again— total trip time, total trip distance, net increase altitude, accumulated increase altitude, maximum traffic speed and average traffic speed.

Because the traffic speed variables were important but not present in all the network segments, the three models have two sub-models, the one applied to the roads with motor traffic and the one applied to streets without motor traffic.

The different OLS regression models performed are based on the analysis of a specific set of cyclists' route arcs (model observations), since they study cyclists' speed according to different variables, and each observation must contain data on all of these variables. This is the reason why more specific samples were selected for the different analyses. The tables in the Results section inform about the number of observations on which each model is eventually based.

6.3.3 Estimation of cyclists' travel times

As stated in the introduction, the analysis of cyclists' operating speeds is crucial for the study of essential aspects of cycling mobility. One of these aspects is the estimation of cyclists' travel times, which at the same time will be the base for subsequent analyses of accessibility and competitiveness. The previous models allow us to predict cyclists' average speed according to different variables at the level of street arc. In this section, we applied the models in order to estimate cyclists' travel times for an entire route (usually made of hundreds of street-network arcs), and we calculated the correlation between real and estimated travel times by the first model (which considers the street-network properties) and the second one (which, in addition, includes other variables related to the trip or the cyclist). It is important to highlight that the models were applied to a number of routes that were not considered when performing the models (control routes). The number of control routes was defined as the 10% of the sample considered when performing the OLS models. This sample consisted of 2,290 routes, so we applied the first and the second models to 229 control routes.

6.3.4 Estimation of cyclists' accessibility and comparison to other transport modes

As an application case for the obtained results, we decided to apply the models in order to perform a comparative analysis of accessibility, in order to find out whether cycling is not only a sustainable transport mode, but also a competitive one.

Different analyses of cycling accessibility have been carried out lately but with a very different focus. For instance, Cycling Accessibility Index (CAI) recently proposed by Saghapour, Moridpour and Thompson (2017), assign accessibility levels in statistical areas by estimating a cost based on the land use and number of activities taking place at these areas. Our goal was not to estimate a new cost but to consider the travel times estimated by the OSL models and measure the cycling accessibility according to them. With this aim, we have calculated areas covered by the isochrones that correspond to a range of travel times (from 5 to 25 minutes, every 5 minutes), for the following transport modes: regular or casual cycling, bicycle-sharing systems (BiciMAD), walking, private car and public transport (using an intermodal network including bus, underground, tram and train). In order to produce comparable results, the isochrones were calculated considering the same street network, applying the same tool —the *Service Area* tool contained in the *Network Analyst* extension of *ArcGIS*— and estimating, for all the transport modes, the average travel times for a weekday morning. The specific methodologies followed when estimating the travel times for each transport mode are described next.

Firstly, cycling isochrones are calculated by considering the estimated cycling speed (and travel time) for each street-network segment estimated by the first OLS regression model, which is considering the variables related to the properties or conditions of the street network (previously listed).

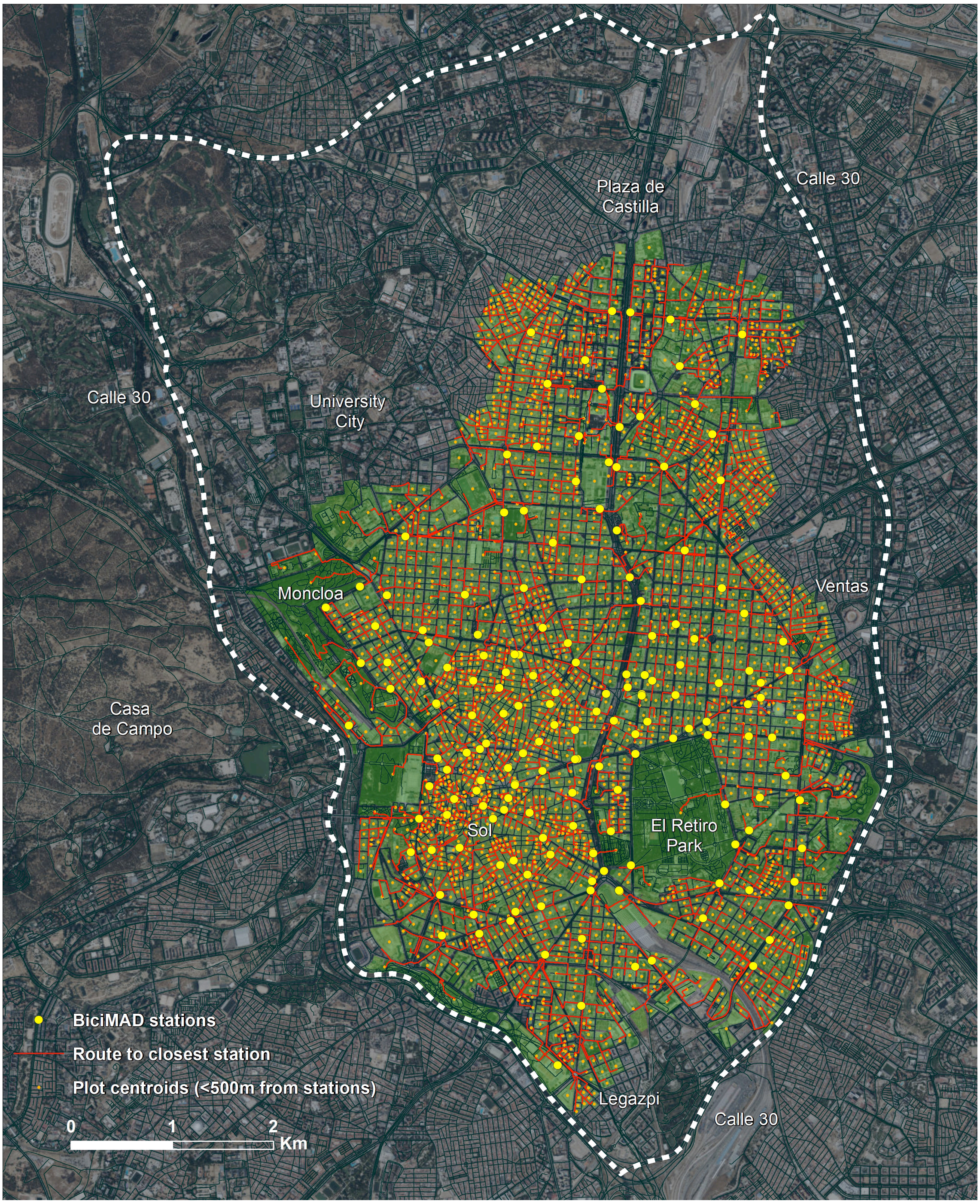
Secondly, for the estimation of walking isochrones we looked at the existing research studies focussed on determining an average walking speed. Bohannon (1997) concluded that mean comfortable gait speed ranged from 127.2 cm/s (4.58 kph) for women in their seventies to 146.2 cm/s (5.26 kph) for men in their forties. Fritz & Lusardi (2009) obtained similar results, establishing the average walking speed between 4.5 - 5.22 kph. Considering these studies, we decided to calculate the pedestrian travel time for each street segment according to a 4.5 kph average walking speed.

Bicycle-Sharing System (BSS) isochrones were calculated considering that BSS users' trips consist of three different stages: the path from the origin to the closest BSS station, the cycling route to the destination station and the path from this station to the final destination. We have considered walking travel times for the first and the last stages, according to the previously defined speeds, and the average BiciMAD frequent users' speed in weekdays mornings (from 7h to 10h), which is, according to the results showed in Section 4, 15.71 kph.

In order to perform a comparative analysis between all different transport modes, we defined Bilbao as the origin of all trips. We have also respected this origin in this case, but, with the aim of performing a more realistic analysis, we have considered not the distance from Bilbao to the closest station (which is null, since there is a BiciMAD station just at this location), but the average distance to the closest BiciMAD station considering the area covered by the BSS so far. In order to do so, we selected the 2563 plots (obtained from the official Cadastre) at less than 500 m from the existing BiciMAD stations, and calculated the average distance to the closest BiciMAD station, using the Closest Facility tool of ArcMap Network Analyst toolbox. The results are illustrated in Figure 6.4. The obtained average distance was 303 metres, and the corresponding average time was 242 seconds (4 minutes and 2 seconds), considering the walking speed previously defined. This means that, for each of the isochrones' defined travel times, we have substracted this time before considering the second stage of the trip, which is the cycling route.

For the third stage of BSS trips, the path from the destination station to the final destination, we have considered the extra time that users have once they have parked their bikes at the final destination, and calculated corresponding travel distance in order to create the final isochrones. Figure 6.8, in the Results section illustrates this clearly.

Figure 6.4: Routes from urban plots' centroids to the closest Bicycle-Sharing System (BiciMAD) station.



Public Transport isochrones were estimated according to the travel times and frequencies considered in the *General Transit Feed Specification* (GTFS) database, obtained from the Regional Transport Consortium of Madrid. By applying the *ArcGIS* tool *Add GTFS to a Network Dataset*, we were able to consider bus, underground, tram and train travel times for a working day at 8:00 am, and run the *Service Area* tool, as we did for the rest of transport modes.

Finally, car isochrones were calculated according to a “door-to-door” approach similar to the one considered by Salonen & Toivonen (2013). This approach estimates not only the travel time spent in the car, but also the average walking time that it usually takes people to arrive to the car, the average time spent looking for a parking place and then, the average walking time from the parking place to the final destination.

Car speed and travel times were taken from the *TomTom*® dataset (*TomTom*® Speed profiles), selecting average weekday morning speed values at 8h, which provides an accurate approach coming from the historical records. Although the average walking distances considered are difficult to estimate since they may greatly vary for each city, for this study, we have considered the 180 distance per walk established by (Kurri & Laakso, 2002), which, at a pace of 4.5 kph, leads to a 288-second travel time considering both walks. When it comes to the time spent looking for parking, we considered the average estimated in the case of Madrid by an study conducted in the city (Europa Press, 2006): 6.28 minutes per trip (376.8 sec/trip). In summary, for the global car travel time estimations we added 664 seconds per trip to the car travel times previously estimated.

6.4 Results

6.4.1 OLS regressions results

6.4.1.1 First OLS regression results: Cyclists’ speed according to street-network properties and conditions

The first OLS regression model estimates an average cycling speed for each street segment according to the network properties. The results are shown in Table 6.2. All the explanatory variables have the expected coefficient signs and the model offers relevant information on the elasticities between these variables and cyclist’s speed. Regarding the sub-model 1.1 (applied to roads with motor traffic), the variables with highest (negative) impact on speed are *Street intersections/km* and *Slope*. In addition, the model is very sensitive to the *Real Average Traffic Speed*, so cyclists seem to feel forced to speed up when riding next to cars circulating faster than on other streets (for example, an increase of 20kph in traffic speed leads to an increase of 3kph in cyclists’ speed on average). Other variables have a significant impact, such as *Traffic Lights/km,* or different bike infrastructure that increase cyclists’ speed (such as *Segregated* or *Non-segregated bike-lanes*) or reduce it (such as Bike-lane on sidewalks).

When it comes to the sub-model 1.2 (applied to roads without motor traffic), the variable with the highest impact on speed is *Slope* rather than *Street intersections/km*, what makes sense considering that probably the presence of traffic is what has the greatest impact when arriving to intersections.

This is the reason why the impact of *Traffic lights/km* is also notably reduced. The impact of slope is relatively lower, probably because traffic pushes cyclists to go faster, also on steep streets. In terms of infrastructure, we find some remarkable differences. Cyclists increase their speed significantly in the different kinds of bike lanes, and even bike lanes on sidewalks, with a negative impact on traffic roads, have a positive impact here.

6.4.1.2 Second OLS regression results: Cyclists' operating speed according to street-network properties and conditions and other aspects related to the trip or the cyclist

The second model assigns an average cycling speed to each route segment according to the street-network and other properties related to the trip or the cyclist and, considering more information, provides a more accurate speed estimation. The results are shown in Table 6.3. The sub-model 2.1 shows the significant different cycling speeds according to gender, females' speed being 2.64kph lower that males'. Although age has a negative influence, its impact is not so important. The purpose of the journey is also a key variable, with some particular purposes having a significant impact compared to the one considered by default in the models (working). Cyclists' speed when traveling for shopping, leisure or errands is lower and higher when sport is the purpose. The *Journey total duration* and the *Journey total elevation gain* have also a negative impact. The influence of the variables related to the street-network properties are similar to those obtained in the first model, with *Slope*, *Street Intersections/km*, *Traffic Lights/km* and *Real Average Traffic Speed* having the greatest impact.

The sub-model 2.2 (applied to roads without motor traffic) reveals some interesting changes. The impact of gender is reduced significantly, so the presence of traffic affects females more than males. The influence of the different purpose of the journey are also reduced and even not any more significant in some cases (sport). The variables related to the street-network properties affects in a similar way as for the 1.2 sub-model.

6.4.1.3 Third OLS regression results: Bike messengers' operating speed according to street-network properties and conditions and other aspects

The third model focuses on bike messengers' routes, and estimates an average cycling speed to each route segment according to the street-network and other properties related to the trip, the conditions (weather) or the type of bicycle. The results are shown in Table 6.4. The data show that bike messengers' average speed is significantly higher than casual cyclists', and sub-model 3.1 reveals some differences in the impact of some variables in relation to casual cyclists' results. Although the factors that affect most messengers' speed are *Slope*, *Street Intersections/km* and *Real Average Traffic Speed*, the impact of *Traffic Lights/km* is not statistically significant. Regarding the type of bike, there is no difference between casual bikes and bullit-bikes (which are electric-assisted), but the average speed of cargo-trikes is dramatically lower. When it comes to the weather, average speeds decrease on cloudy days, and especially on rainy days.

Sub-model 3.2's results show some differences compared to the previous one. Average speed is significantly higher, the influence of bad weather is not statistically significant (so what truly affects bike messengers is the combination of bad weather and motor traffic), the impact of intersections decreases by 50%, although the impact of traffic lights increases significantly, probably due to the fact that, even if messengers' speed were similar to the previous one at intersections, the reduction is higher simply because the average circulating speed is also higher. When it comes to the type of bike, cargo-trikes' average speed is much closer to the casual bicycle's, which means that what probably makes it slower on roads with traffic is the difficulty of circulating along with cars. Bullit-bikes' average speed is clearly higher here, too. The effect of cloudy and rainy days is slightly reduced.

Table 6.2. First OLS regression model results: Cyclists' speed according to street-network properties and conditions.

Sub model 1.1 (roads with motor traffic)				
Independent variables	Coefficient	Std. Error	Robust_t	Robust_Prob
Intercept	13.896526	0.143329	99.5122	0,000000*
Street Intersections / km	-0.110078	2.302086	-50.3755	0,000000*
Slope (percent rise)	-0.614379	0.011783	-48.8691	0,000000*
Real Average Traffic Speed (kph)	0.149815	0.003918	35.8919	0,000000*
Traffic Lights / km	-0.038570	3.241606	-11.9528	0,000000*
Bike lane on the sidewalk *	-0.764160	0.111472	-7.3131	0,000000*
Max. Traffic Speed (kph)	0.023694	0.003173	7.1872	0,000000*
Non-segregated bike lane	1.087164	0.178602	6.4770	0,000000*
Segregated bike lane in parks with a minimum adapted surface	2.577820	0.784055	2.0559	0,039795*
Segregated bike lane in parks without adapted surface	-	-	-	-
Segregated bike lane in parks with adapted surface.	-	-	-	-
Adjusted R-Squared:	0.430794			
Number of explanatory variables:	8			
Number of Observations:	14,144			
Joint F-Statistic:	1071.387062			
Prob(>chi-squared):	(8) degrees of freedom: 0.000000*			
Sub model 1.2 (roads without motor traffic)				
Independent variables	Coefficient	Std. Error	Robust_t	Robust_Prob
Intercept	14.946825	0.288699	49.6819	0,000000*
Street Intersections / km	-0.058972	3.768646	-15.5466	0,000000*
Slope (percent rise)	-0.727377	0.024195	-27.9843	0,000000*
Real Average Traffic Speed (kph)	-	-	-	-
Traffic Lights / km	-0.084582	6.742596	-12.2231	0,000000*
Bike lane on the sidewalk *	1.413114	0.273998	4.96793	0,000001*
Max. Traffic Speed (kph)	-	-	-	-
Non-segregated bike lane	6.118493	0.918732	6.5874	0,000000*
Segregated bike lane in parks with a minimum adapted surface	2.653539	0.283496	8.7532	0,000000*
Segregated bike lane in parks without adapted surface	2.232850	0.269059	7.8334	0,000000*
Segregated bike lane in parks with adapted surface.	4.766114	1.778681	2.4405	0,014707*
Adjusted R-Squared:	0.38055			
Number of explanatory variables:	8			
Number of Observations:	3,325			
Joint F-Statistic:	3325			
Prob(>chi-squared):	(8) degrees of freedom: 0.000000*			

* An asterisk next to a number indicates a statistically significant p-value (p < 0,01).

** Dummies by default: Working (Purpose-journey), Male (Gender), Normal bike (Type of bike), Sunny (Weather), No infrastructure (Bike inf.).

Table 6.3: Second OLS regression model results: Cyclists' operating speed according to street-network properties and conditions and other aspects related to the trip or the cyclist.

Sub model 2.1 (roads with motor traffic)				
Independent variables	Coefficient	Std. Error	Robust_t	Robust_Prob
Intercept	16.125669	0.209471	75.8568	0,000000*
Slope (percent rise)	-0.640976	0.010899	-55.1229	0,000000*
Street Intersections / km	-0.103477	2.113076	-50.5520	0,000000*
Real Average Traffic Speed (kph)	0.150352	0.003632	39.2280	0,000000*
Female **	-2.646586	0.104986	-25.6895	0,000000*
Traffic Lights / km	-0.035146	2.956057	-11.5618	0,000000*
Bike lane on the sidewalk **	-1.065185	0.106452	-10.7998	0,000000*
Shopping (Purpose of the journey) **	-1.194894	0.141346	-8.6254	0,000000*
Leisure (Purpose of the journey)	-0.712665	0.082558	-8.4998	0,000000*
Age	-0.031367	0.004139	-7.5427	0,000000*
Journey accumulated elevation gain	-0.000615	0.000092	-6.3306	0,000000*
Non-segregated bike lane	0.781634	0.163407	5.2324	0,000000*
Sport (Purpose of the journey)	0.705940	0.134400	5.1844	0,000000*
Max. Traffic Speed (kph)	0.013483	0.002956	4.4226	0,000013*
Journey total duration (minutes)	-0.009422	0.001116	-3.7263	0,000208*
Errands (Purpose of the journey)	-0.425247	0.154442	-2.4794	0,013160*
Segregated bike lane in parks or countryside without adapted surface	1.729533	0.754446	1.7943	0.0728
Adjusted R-Squared:	0.507344			
Number of explanatory variables and observations:	16	13,195		
Joint F-Statistic:	648.016818			
Prob(>chi-squared):	(16) degrees of freedom: 0.000000*			
Sub model 2.2 (roads without motor traffic)				
Independent variables	Coefficient	Std. Error	Robust_t	Robust_Prob
Intercept	16.324385	0.368436	41.6686	0,000000*
Slope (percent rise)	-0.733187	0.021270	-30.9484	0,000000*
Street Intersections / km	-0.050306	3.330511	-14.4269	0,000000*
Female **	-1.934628	0.175829	-11.5843	0,000000*
Traffic Lights / km	-0.080122	5.982404	-13.1951	0,000000*
Bike lane on the sidewalk **	1.267616	0.239712	4.9765	0,000001*
Shopping (Purpose of the journey) **	-0.812899	0.137930	-6.1796	0,000000*
Leisure (Purpose of the journey)	-0.416404	0.132091	-3.0737	0,002146*
Age	-0.033771	0.007809	-4.1050	0,000048*
Journey accumulated elevation gain	-0.000706	0.000174	-3.6613	0,000269*
Non-segregated bike lane	5.024177	0.796331	6.0131	0,000000*
Journey total duration (minutes)	-0.090122	0.004656	-14.1447	0,000000*
Errands (Purpose of the journey)	-0.617354	0.234837	-2.4956	0,012614*
Segregated bike lane in parks or countryside without adapted surface	1.777535	0.240033	6.8491	0,000000*
Segregated bike lane in parks with a minimum adapted surface	1.741134	0.255245	6.3931	0,000000*
Study (Purpose of the journey)	-0.499587	0.187293	-2.6999	0,006970*
Journey total Elevation gain	-0.001159	0.000464	-2.3155	0,020634*
Adjusted R-Squared:	0.508577			
Number of explanatory variables and observations:	16	3,145		
Joint F-Statistic:	172.24974			
Prob(>chi-squared):	(16) degrees of freedom: 0.000000*			

* An asterisk next to a number indicates a statistically significant p-value ($p <$ 0,01).

** Dummies by default: Working (Purpose-journey), Male (Gender), Normal (Type of bike), Sunny (Weather), No infrastructure.

Table 6.4: Third OLS regression model results: Bike messengers' operating speed according to street-network properties and conditions and other aspects.

Sub model 3.1 (roads with motor traffic)				
Independent variables	Coefficient	Std. Error	Robust_t	Robust_Prob
Intercept	18.690917	0.493495	38.1979	0,000000*
Slope (percent rise)	-0.809405	0.042253	-18.9618	0,000000*
Street Intersections / km	-0.204808	11.385619	-18.8879	0,000000*
Real Average Traffic Speed	0.174849	0.012174	13.8727	0,000000*
Cargo Trike (Type of bike) *	-6.951373	0.625673	-13.3828	0,000000*
Journey accumulated elevation gain	-0.008695	0.001478	-5.9054	0,000000*
Journey total distance (m)	-0.000141	0.000034	-4.0109	0,000070*
Cloudy (weather conditions) *	-0.813709	0.224755	-3.5540	0,000403*
Journey total duration (minutes)	-0.002584	0.000967	-3.2045	0,001389*
No infrastructure but cycling preference and speed reduction *	-0.945501	4.822533	-3.0121	0,002637*
Rain (weather conditions)	-1.632137	0.628736	-2.5375	0,011228*
Traffic Lights / km	0.021714	16.053513	1.1991	0.2306
Bike lane on the sidewalk	-0.552554	0.596600	-0.9321	0.3514
Max. Traffic Speed	0.010340	0.010860	0.9278	0.3536
Bike lane on the sidewalk	0.323160	1.293699	0.2660	0.7903
Bullit Bike (Type of bike)	0.126777	0.450148	0.2430	0.8080
Journey total Elevation gain (m)	-0.000418	0.001945	-0.2288	0.8191
Adjusted R-Squared:	0.404826			
Number of explanatory variables and observations:	16	2092		
Joint F-Statistic:	89.891309			
Prob(>chi-squared):	(16) degrees of freedom: 0.000000*			
Sub model 3.2 (roads without motor traffic)				
Independent variables	Coefficient	Std. Error	Robust_t	Robust_Prob
Intercept	23.157555	0.755333	31.8712	0,000000*
Slope (percent rise)	-0.771806	0.086452	-8.4907	0,000000*
Street Intersections / km	-0.101624	17.422687	-5.5983	0,000000*
Cargo Trike (Type of bike) *	-1.000872	2.792684	-2.6556	0,008133*
Journey accumulated elevation gain	-0.004022	0.002648	-1.5144	0.1305
Journey total distance (m)	-0.000594	0.000062	-8.5790	0,000000*
Cloudy (weather conditions) *	-0.638994	0.255319	-2.4774	0,013511*
Journey total duration (minutes)	-0.101541	0.006720	-14.0378	0,000000*
Rain (weather conditions)	-1.512201	1.082510	-0.8941	0.3716
Traffic Lights / km	-0.246487	36.921162	-6.9825	0,000000*
Bike lane on the sidewalk	-2.372282	0.787919	-2.9815	0,002999*
Bullit Bike (Type of bike)	4.219074	1.039736	3.3325	0,000931*
Journey total Elevation gain (m)	-0.000963	0.002178	-0.4652	0.6420
Segregated bike lane in parks without adapted surface.	-2.814815	0.716738	-4.0749	0,000059*
Segregated bike lane in parks with a minimum adapted surface	-2.345925	1.091353	-2.2275	0,026287*
Adjusted R-Squared:	0.523833			
Number of explanatory variables and observations:	14	586		
Joint F-Statistic:	46.968672			
Prob(>chi-squared) 14 degrees of freedom:	0.000000*			

* An asterisk next to a number indicates a statistically significant p-value (p < 0,01).

** Dummies by default: Working (Purpose-journey), Male (Gender), Normal (Type of bike), Sunny (Weather), No infrastructure.

6.4.1.4 General remarks on the OLS regressions results

In order to understand the OLS R-squared results, some caveats must be taken into account. The dependent variable that we are modelling is cyclists' speed at a specific route segment, and the R-squared 'modest' values obtained can be explained by factors of a different nature. First, there are aspects related to changing conditions on the street segments over time that dramatically affect cyclists' speed. Speed at a specific road segment will be completely different whether cyclists arrive to a green traffic light or to a red one, or whether they find traffic or not at non-signalized intersections. Then, there are other factors related to the particular conditions of the cyclists, personal variables related to physical condition or health, as well as to the type of bike they are riding (road bikes, foldable bikes, mountain bikes, etc.). Actuality, similar OLS R-squared results were obtained (R^2=0.414) when analysing walking speeds (Bohannon, 1997), especially when considering the potential variables with impact on such a complex functional activity (Fritz & Lusardi, 2009), which, therefore, is less predictable than other transport modes.

In any case, the first type of these factors affects the estimation of cyclists' speed at a particular route segment, but not when considering an entire route, which is usually made of hundreds of segments. At the end of the trip, the number of red or green traffic lights found will probably be balanced, as well as the number of intersections with or without traffic, so when analysing the estimated vs. real trip travel times (next section), the global performance of the model will be much better.

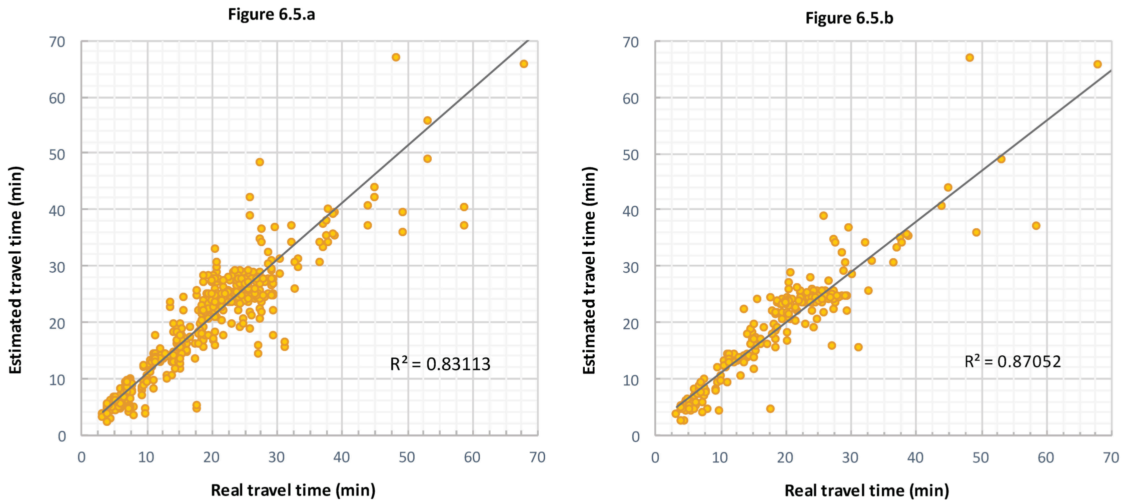
6.4.2 Global performance of the model: Estimated vs. real travel times for an entire route

Although the previous models showed moderate R-squared values when predicting cyclists' speed at a particular route arc (for the reasons already mentioned), the performance of these models when predicting cyclists' travel times for an entire route, which is usually made of hundreds of segments, is much better.

Figure 6.5a illustrates the correlation between real travel times and the time estimated by the first model (R^2=0.83), which considers the street-network properties, and Figure 6.5b shows the correlation obtained by the second model (R^2=0.87), which, in addition, includes others variables related to the trip or the cyclist. Both correlations are obtained for a sample of 229 control routes (routes that were not considered when performing the models).

The results obtained by the first model show how accurate the estimations of travel times may be when merely considering the street-network properties. The second model improves the estimation but, given the additional number of variables that it considers in comparison with the previous one, it also shows a clear limitation when predicting cyclists' operating speeds. This is not an unexpected result, since it seems reasonable to expect slightly different travel times even for the same trip completed by two different persons with similar characteristics and the same purpose of the journey.

Figure 6.5: correlation between real and estimted travel times according to the first (a) and the second model (b)



6.4.3 Application case: Estimated cyclists' accessibility and comparison to other transport modes

In this section, we perform a comparative analysis of accessibility and competitiveness between different transport modes, by calculating the isochrones that correspond to a range of travel times (from 5 to 25 minutes, every 5 minutes), for all the existing transport modes in Madrid: casual or regular cycling, Bicycle-Sharing Systems, walking, private car and public transport (using an intermodal network, including bus, underground, tram and train). Cycling travel times were estimated by applying the first OLS model (according to street-network properties and conditions). Table 6.5 shows the area that corresponds to each isochrone (the urban area covered by each transport mode, according to the defined range of travel times), Figure 6.6 illustrates these relationships and Figure 6.7 illustrates the isochrones on different maps, at the same scale, so they can be easily compared.

Table 6.5: Area covered (Ha) according to travel time and transport mode

Journey duration (minutes)	5	10	15	20	25
Walking Area Covered	52.06	161.22	347.72	587.06	906.66
BiciMAD Area Covered	6.47	371.91	1,259.32	2,286.72	3,228.47
Cycling Area Covered	343.38	1,283.03	3,048.72	5,396.81	8,516.78
Car Area Covered	0.00	0.00	585.75	4,229.03	15,161.81
Public Transport Area Covered	106.84	741.97	2,061.75	4,635.63	9,017.16

The results reveal that cycling is not only a sustainable transport mode, but is also the most competitive for small-medium distances, with Figure 6.6 clearly illustrating the better performance of cycling (in terms of the area covered) for trips under 21 minutes in length for the centre of Madrid.

For trips over 21 minutes in length, the car begins to be more competitive, but only if we do not consider areas where private cars are forbidden, which is increasingly common in the central areas of many cities. For trips over 23 minutes in length, Public Transport begins to be more competitive, as well. In any case, long-distance trips often involve different transport modes, so the results should raise awareness about the suitability of promoting cycling as part of these multimodal trips.

The previous consideration of cycling as the most competitive for small-medium distances (under 21 minutes) refers to casual or regular cyclists' mobility. With regard to Bicycle-Sharing System (BiciMAD) users, the results are substantially different. The area covered by BiciMAD isochrones is much lower, as Table 6.5 and Figures 6.6 and 6.7 illustrate. Considering that BiciMAD users' average speed is quite similar to regular cyclists' one when commuting, this fact is explained by other reasons. The first one has to do with the current BiciMAD system extension, which covered area is limited by the location of the existing BiciMAD stations (see Figure 6.7.2). The second reason that explains the low values of BiciMAD accessibility is the fact that BSS users' trips consist of three different stages: the path from the origin to the closest BSS station, the cycling route to the destination station and the path from this station to the final destination. Only the second stage correspond to a cycling route, while walking has been considered for the first and the last stages. As explained in the methodology section, we have taken into account these three stages, and considered a first walking path to the closest BiciMAD station, which average distance was estimated in 303 metres, with a corresponding average time of 242 seconds (4 minutes and 2 seconds), before BiciMAD users start to cycle. Then, for the final stage we have considered also walking. Figure 6.8 aims to illustrate all these facts, helping understand the definition of the isochrones.

Figure 6.6: Area covered (Ha) according to travel time and transport mode

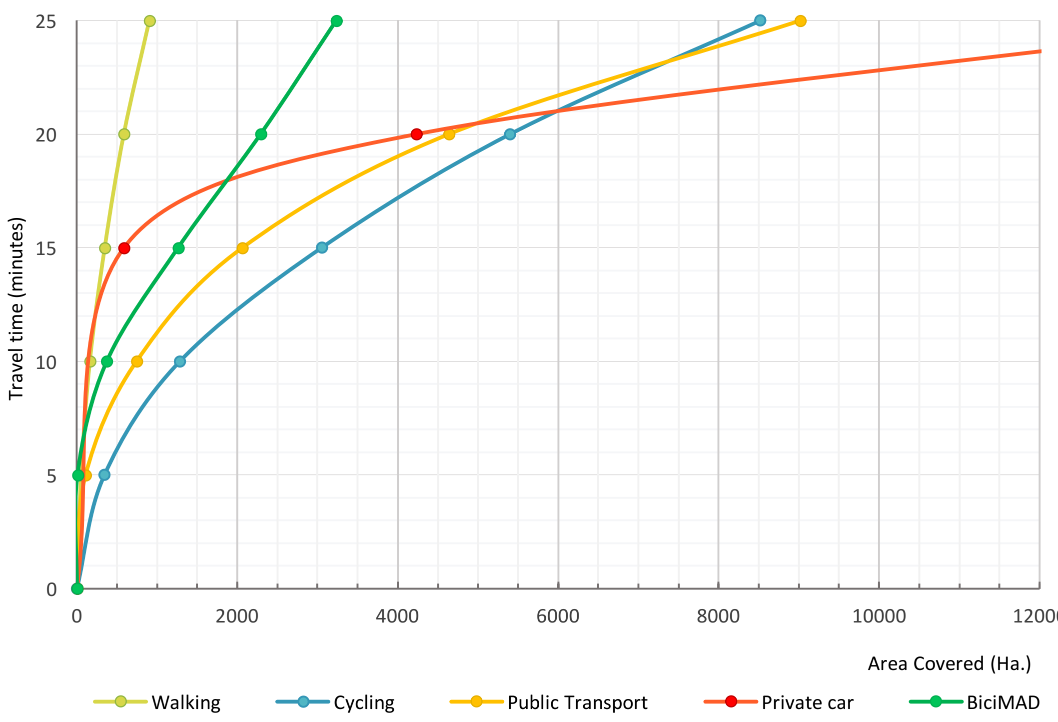


Figure 6.7: Isochrones according to transport mode: Walking (1), Bicycle-Sharing System (BiciMAD) stations (2) and isochrones (3), casual cycling (4), Public Transport (5) and Private Car (6).

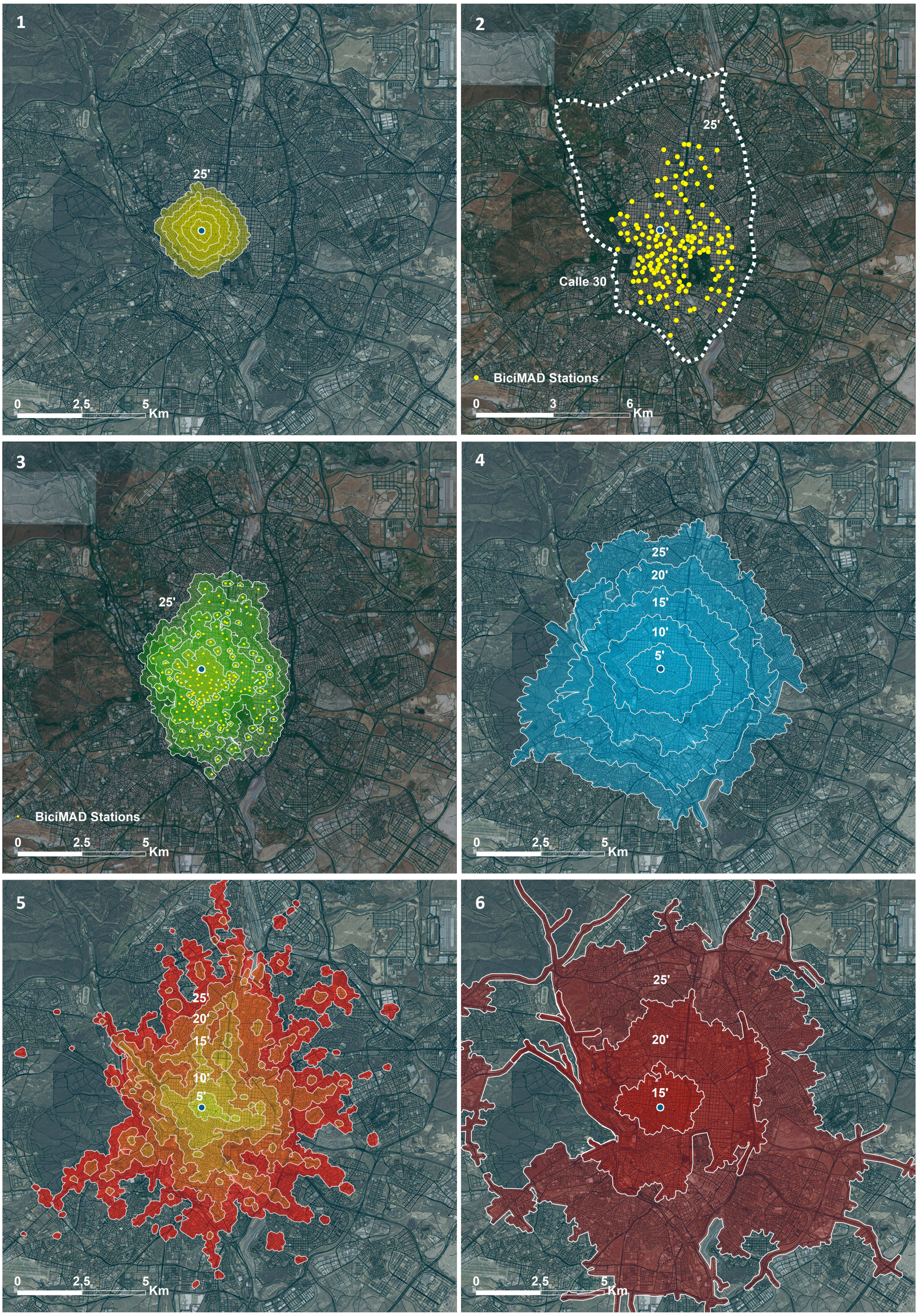
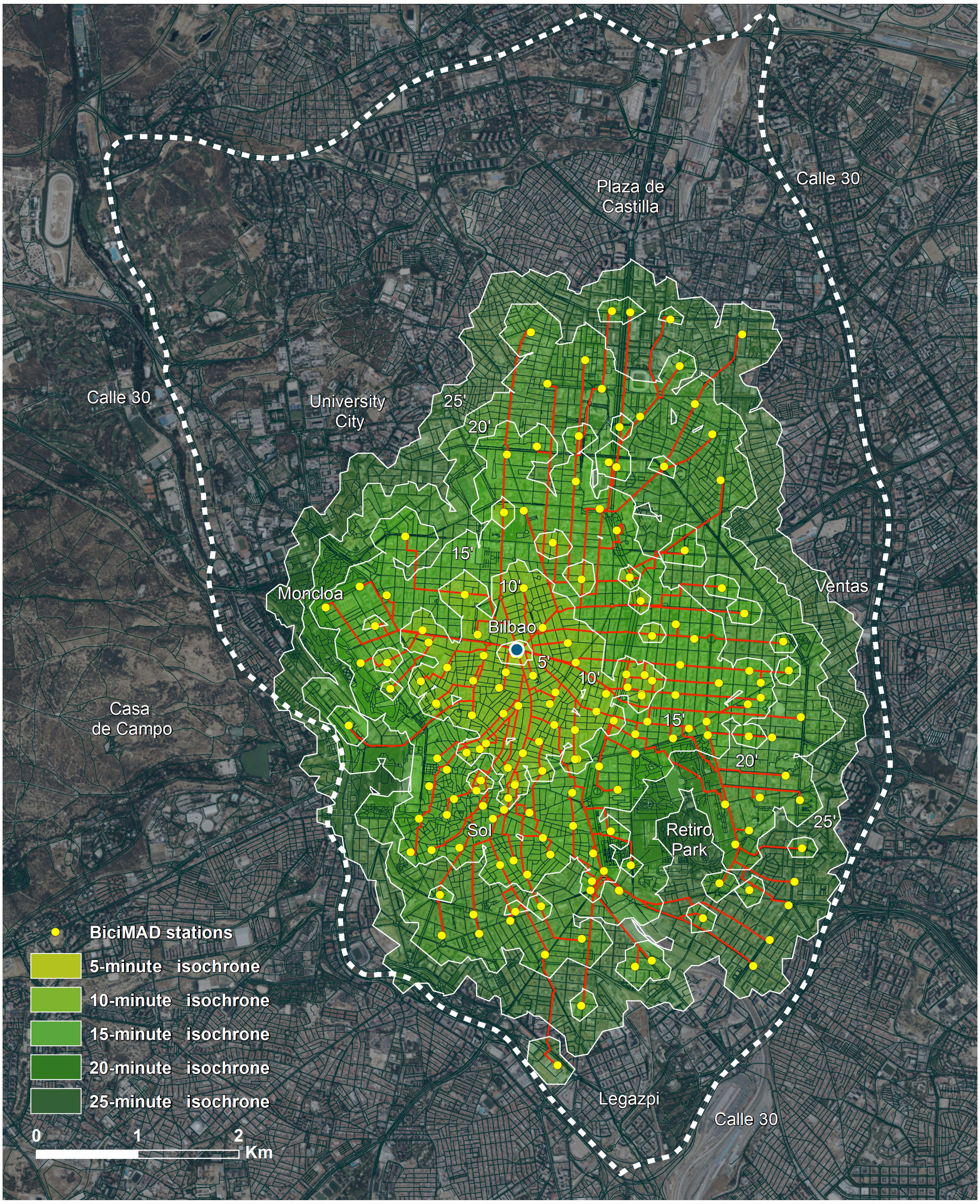


Figure 6.8: BiciMAD isochrones (5, 10, 15, 20, and 25 minutes)



6.5 Conclusions

The famous quote by the American cyclist John Howard (1987), "*The bicycle is a curious vehicle. Its passenger is its engine,*" highlights an important fact for this study. Cycling mobility is extraordinarily complex because these human engines are affected by a wide range of factors, physical, social and psychological factors (Willis et al., 2015), that can have a different impact on each individual, since humans may behave differently under similar circumstances. This paper studies cyclists' operating speeds embracing this complexity, by analysing the impact of a wide variety of variables at the same time.

The results obtained support Howards' declaration, and present cycling as a particular transport mode, sensitive to many elements. The OLS models shed light on the influence of a wide range of factors on cyclists' speed, quantifying the specific impact of a wide range of variables of a different nature: from the street-network properties to other properties related to the trip (such as the purpose of the journey) or the cyclist (such as gender or age). Although the different models show modest R-squared values when predicting cyclists' speed at a particular route segment (for the reasons previously discussed), the models performed quite well when predicting cyclists' travel times for an entire route (usually made of hundreds of segments), showing a high correlation between estimated and real travel times for both the first model (R^2=0.83), which considers the street-network properties, and the second model (R^2=0.87), which, in addition, includes other variables related to the trip or the cyclist. Although this second model improves the travel time estimations, it also shows certain limitations when predicting cyclists' operating speeds, an expected result, since it seems reasonable to obtain slightly different travel times for the same trip completed by two different cyclists with similar characteristics and the same purpose for the journey.

Another relevant output is that the models also allow us to estimate cyclists' travel times for the entire street network and not only in the street-network arcs where we have cyclists' records (just 30% of the total) and, furthermore, they also allow us to predict cyclists' travel times and accessibility in future scenarios, given certain changes in the network, such as the execution of new infrastructure or implementation policies, such as slowing down traffic speed. In consequence, the models can be considered as tools that may help decision makers when evaluating future scenarios.

Finally, this accurate estimation of cyclists' travel times also allows us to conduct the comparative analysis of accessibility, and evaluate competitiveness between different transport modes. The results show that cycling is the most competitive transport mode for small-medium distances (under 21 minutes in length for Madrid), which is a relevant finding not only for casual cycling mobility, but also for bike-driven parcel delivery service, since bike-messenger performance is even greater than casual cyclists'. Therefore, a consequent goal of this paper has become to raise awareness of cycling, not only an environmentally-sustainable transport mode, but also as the most efficient mode for an important range of distances. The same analysis also evidence the limited accessibility provided by BiciMAD (Madrid Bike-Share System) essentially due to its current level of implementation, covering only the core of the city of Madrid.

Future research should cover one of the most important limitations of this study; it should expand the cyclists' routes sample and include the analysis of the GPS tracks coming from the Madrid Bike share system, whose electric bikes are being used by an increasing number of people. E-bikes used by casual cyclists should be also included and analysed. In this case, it is expected that the different factors studied in this research affect cycling speeds and travel times in a different way (for instance, the impact of slope), so a comparative analysis would allow us to measure and model these differences. Another important limitation to highlight is that this study focuses on one single city. The impact of the variables analysed will probably be different in other cities. Future research would have to explore other cities and compare the results, so that stronger and more consistent findings will arise.

7 Conclusions and future research lines

7.1 Conclusions

This thesis comprises diverse research papers including their corresponding conclusion sections. The aim of this chapter is not to repeat these specific conclusions related to each paper, but to provide more general ones from a perspective that understands this thesis research as a whole. The conclusions are provided in relation to the specific research questions and objectives defined in the Introduction section. Finally, some general conclusions, related to the main objective of this research are also delivered.

7.1.1 Conclusions regarding the research specific questions and objectives

Nine research questions to address were defined when this thesis research was planned. We described them in the Introduction section and, in addition, we defined a number of research objectives, derived from and related to these research questions. The aim of this section is to provide the main conclusions that can be drawn based on the research conducted. These conclusions are provided next, in relation to each specific objective.

RQ1. What is the relevance of analysing the spatial dimension of cycling mobility and, more specifically, cyclists' routes and cycling flow across the city?

Exploring cycling flow across the city is crucial in order to understand different aspects of cycling mobility, and provide relevant information to be considered when planning policies and infrastructure. In this sense, the analyses carried out and the results obtained in this thesis indicate a number of specific applications and contributions at different levels.

First, we can identify the most important urban streets in terms of cycling flow. In the case of Madrid Bike Share System, it was possible to count the average number of cyclists riding daily along a specific street. In the case of casual cyclists or bike messengers, we do not have the total number of routes, but a sample that was not enough to estimate cycling flow distribution across the whole city network. In any case, a general picture is provided, and working on route choice models could help us to better estimate the potential distribution of casual cyclists and bike messengers' cycling flow, as we will discuss later on. It is really important to measure this cycling flow across the city network and its evolution over time, since it is the base for other analyses that we are describing next.

Second, given the fact that it is possible to estimate cycling flow along every urban street, it is possible to monitor the real use of cycling infrastructure. Cities all around the world are investing an important amount of money in implementing different types of infrastructure. To what extent they are effective? Are they really changing cyclists' behaviour? Are they really channelizing and supporting an important cycling activity? What kind of cycling infrastructure are being more attractive to cyclists? What kind of factors make the different types of infrastructure more or less successful? The preference for segregated bike lanes might be different in streets with high level of motor traffic than in quite urban areas in terms of traffic, for instance. We will discuss all this with further detail later, but it is fundamental to highlight here the importance of measuring constantly the impact of infrastructure in order to improve our understanding and future planning of such infrastructure and policies.

Third, by analysing cyclists' routes we can also study the factors that have an important impact on cyclists' route choice. Why do cyclists choose a particular path and discard the other alternatives? Are there common patterns in the preference of certain paths? What are the factors that have more impact in this choice? What is the impact of motor traffic flow or speed, for instance? Although these are not questions address in this thesis, and are part of the future research lines that we will describe in the next section, it is important to highlight here the relevance that the analysis of cycling routes may have in this sense.

In addition, the spatial analysis of cycling mobility and more specifically, the analysis of cyclists' flow distribution, can shed some light on the analysis of the factors that have an important impact on cyclists' safety. The geolocation of cyclists' accidents is commonly registered in urban areas, and the analysis of these geo-located accidents in relation to the distribution of cycling flow is crucial in order to understand what areas can be considered as unsafe.

Finally, the spatial analysis of cycling mobility is, considering the different applications previously described, absolutely relevant to planning a policy making. The analysis of existing cycling flow can be derived into models that will be able to predict the potential cycling flow along streets were a certain type of infrastructure or certain policy (such as calming down traffic) can be implemented, so these analyses and these models will be hopefully considered in order to define better policies and implement more efficient infrastructure. Also the data collected form casual cyclist and the analyses derived from the, provide important information on the use bicycles for commuting to work, for instance, which can be the base for defining future policies or agreements with companies in order to stimulate this mobility and plan the best cycle infrastructure to foster it, such as the location of bike stations of bike parking. Finally, the analysis of cycling mobility according to the different socio-demographic profiles can also be the base for the formulation of policies and measures aimed at stimulating cycling among specific socio-demographic groups and reduce existing imbalances, such as the gender one.

RQ2. What is the current understanding of the spatial dimension of cycling mobility?

In order to address this question, we defined as a first objective to review the existing literature on the spatial analysis of cycling mobility and the study of cyclists' routes and travel patterns. From the review conducted, we confirmed the idea that, although over the past years a significant number of studies have analyses cycling mobility, we know very little about the way cyclists move around in cities. As we described in Section 2, several studies were focussed on the study of the role of infrastructure on cycling mobility or the analysis of cycling route choice, but most of them were based on data obtained through counts or other dominant techniques such as Stated and Revealed Preference methods. As described in the review, these traditional techniques presented remarkable limitations in terms of high costs, small samples and spatial imprecision (Hood et al., 2011), and therefore, the understanding of the mentioned questions (the role of infrastructure on cycling mobility or the analysis of cycling route choice) presented important limitations as well.

In any case, other aspects studied in this thesis still remained unexplored, such as the analysis of cyclists' speeds according to different factors affecting such speed, and the derived estimations of cycling travel times that eventually allowed to perform analyses of accessibility and comparative analyses of competitiveness between different transport modes.

RQ3. What are the new research opportunities that new data sources on cycling mobility are offering?

As introduced in the background section, the reason why the spatial dimension of cycling mobility had not been properly explored yet was essentially the almost inexistence of data that could support this kind of analysis. As part of the review of the state of the art process, we decided to perform an up to date exploration of the new data sources that that are becoming increasingly accessible to researchers and policy makers, and then, to study the emergent research studies based on these new data, most of which have been conducted over the last ten years.

The review, synthesised in the paper *Big Data and cycling* (Romanillos et al., 2015), allowed us to identify the emergent research lines based on the exploration of these new datasets, and to have a panoramic view of the techniques, objectives and findings of the growing number of studies that we classified into three groups according to the nature of the data they are based on: GPS data (spatio-temporal data collected using the global positioning system (GPS)), live point data and journey data. The paper discusses the movement from small-scale GPS studies to the 'Big GPS' data sets held by fitness and leisure apps or specific cycling initiatives, the impact of Bike Share Programmes (BSP) on the availability of timely point data and the potential of historical journey data for trend analysis and pattern recognition.

But, in addition, the review also allowed us to identify the research gaps, to understand the different value, research potential and limitations of the diverse types of dataset collected in the context of this thesis, and to define what could be our contribution to the existing research.

In this sense, the data collected through the *Huella Ciclista de Madrid* initiative can be considered a small sample of GPS routes, compared to the real number of routes that cyclists daily do in Madrid. In consequence, although the digital footprint that corresponds to the GPS tracks reveals what are the most important streets in terms of cycling flow, the sample is not enough to get an exact picture of the cycling flow distribution across the whole city network. Furthermore, the number of routes collected by the initiative is really low compared to the number of routes collected through commercial apps such as *Strava*, *Wikiloc* or *Endomondo*. However, the data collected through the *Huella Ciclista de Madrid* initiative is really valuable for certain research purposes. First, we can analyse each GPS route independently, while some of the data provided by certain apps correspond to aggregated data (in the case of Strava Labs, for instance), and this fact allowed us to perform different analyses such as the analysis of cycling speeds according to a wide range of local factors that correspond to the street characteristics of the different route segments studied. Second, the sample provides important socio-demographic information associated to each route, such as age, gender or data related to the trip such as the purpose of the journey, data that cannot be provided (in case they have it) by commercial apps companies, because of personal data protection reasons. This information associated to each route allowed us to study the different cycling mobility patters according to age, gender, the purpose of the journey, offering important information to be considered for planning and policy-making purposes, for instance. Finally, regarding the study of the distribution of casual cyclists or bike messengers' cycling flow, although the sample is not enough to offer a clear picture, it is actually enough to develop a route choice model and eventually estimate the potential distribution of cycling flow, given a demand and an Origin-Destination Matrix, something out of the scope of this thesis but contemplated as one of the future research lines we are interested in, as we will discuss later.

In the case of the dataset obtained from BiciMAD, the Madrid Bike-Share System, the value and research potential of the sample is completely different. It does not make sense in this case to talk about the size of the sample, since the sample actually correspond to the total amount of BiciMAD trip, limited in this particular case to a month period, as a decision made for processing reasons, not because a limitation to the access of data. In consequence, the estimation of the distribution of cycling flow across the city network correspond to the real picture of BiciMAD activity, allowing us to identify not only what are the most important urban arteries in terms of cycling flow, but also the activity for any street. This information is quite important in order to evaluate the levels of use of certain cycling infrastructure, for instance. In addition, the routes are being constantly registered, so it is possible to monitor the evolution of cycling flow over time, opening the possibility of evaluating the impact of policies an infrastructure.

However, the information associated to each route is quite limited. We have information about age (age ranges) but not about gender, and we do not know what is the purpose of the journey for each route. In addition, the GPS tracks have a low temporal resolution (an average interval of 75 seconds) compared to the one typically obtained with commercial smartphone apps or GPS devices (Romanillos and Zaltz Austwick 2015), which tends to be around 2 seconds, as it is in the case of the *Huella Ciclista de Madrid* sample. In consequence, the real map-matched route lines had to be estimated as the shortest path between the track points, and it is not possible to perform certain analyses, such as the detailed study of cyclists' operating speeds conducted in this thesis for casual cyclists and bike messengers, based on the *Huella Ciclista de Madrid* sample.

We conclude then that every kind of dataset offers different research possibilities, and future advances will be probably based on the analysis of combined information coming from different sources, following the Big Data principle of *Variety* –one of the three Laney's (2001) "3Vs" principle the Big Data meets: volume, velocity and variety–. As discussed in Big Data and cycling (Romanillos et al., 2015), the recent collaboration between commercial Apps and planning institutions is promising and will generate combined and useful information that will make new explorations possible. Big Data will not substitute but complement other more conventional sources, since they often lack disaggregate data on the cyclists, which are so often necessary to understanding the contexts that influence many of their decisions.

RQ4. What paths do cyclists follow? What are the most important urban arteries in terms of cycling flow? How is cycling flow distributed across the urban street-network? How can we measure this flow distribution?

As advanced in the background section, the study of cyclists' real routes is relevant at two different levels: at the individual level, since it is important to know the paths that cyclists use to follow and what are the factors that have a greater impact in their journey, and at the level of the urban scale, when analysing how cycling flow is distributed across the city network. The conclusions regarding the first level will be discussed with further detail later, in relation to other research questions, so now we can focus on the conclusions that can be drawn in relation to the second question.

In this thesis, we have estimated the distribution of the cycling flow derived from BiciMAD activity, based on the previous estimation of the individual map-matched routes obtained from processing the GPS tracks registered by the Bike-Share System. After this process and based on this estimation, we have analysed the distribution of cycling flow derived from BiciMAD, from three different perspectives and obtaining three different outcomes.

First, the average number of cycling routes that correspond to each street network segment has been calculated and visually represented on maps that illustrate the levels of cycling flow for the whole urban street network, according to different moments (weekdays and weekends). These maps allow us to identify easily the most important streets and axes in terms of cycling flow, and are very effective tools that make us easy to understand the general patterns and mobility behaviour of the city.

However, these maps do not allow us to answer some important questions that can be raised when studying the distribution of cycling flow. To what extent cycling flow is distributed across the city network? Is the obtained cycling flow generally distributed or concentrated in certain urban areas or axes? How can we measure this level of concentration so that we can monitor the evolution over time or compare different cities? With the aim of responding to these questions, we defined a second output, a graph that represents the percentage of street network segments that supported different amounts of cycling flow (Figure 4.10), revealing how concentrated cycling flow is in Madrid, and offering the possibility of comparing this graph to the graph of other case studies and draw some conclusions. We guess there are cities with high cycling flow concentrated in a few streets others where cycling flow is more distributed. Whether cities with a more important cycling culture respond to one model or the other, can be analysed, studying also the relationship of a higher of lower distribution of cycling flow with the more or less distribution of cycling facilities.

Finally, a third outcome regarding the analysis and evaluation of cycling flow distribution is proposed in this thesis, with the aim of determining the cycling flow “captured” or “supported” by streets with cycling infrastructure. The outcome consists on calculating the previous estimation (the percentage of street network segments that supported different amounts of cycling flow) considering independently the streets with segregated bike lanes (Vías ciclistas) and the ones where road bike lanes —non-segregated from traffic— (Ciclocarriles) have been implemented. These graphs, together with the previous one, are illustrated in Figure 4.10 for the case of Madrid.

What is the percentage of cycling flow “captured” or “supported” by streets with cycling infrastructure in cities like Amsterdam or Copenhagen? The definition of these graphs, understood as particular signatures of the existing cycling mobility of each city, or considering the same city in different moments (evolution over time) is important if order to have some “objective” indicators that can allow us to track and monitor the impact of the implementation of different policies or infrastructure.

The analysis of the distribution of cycling flow carried out in this thesis is just focussed on the cycling flow derived from BiciMAD, since, as previously stated, the *Huella Ciclista de Madrid* initiative sample is not enough to get an exact picture of the cycling flow distribution across the whole city network.

An estimation of casual cyclists' flow could be obtained in two different ways. The first one could be to re-launch the *Huella Ciclista de Madrid*, or a similar initiative, with the support of local institutions and cycling associations, with the aim of getting a greater sample, and maintain the activity so that routes are constantly collected and casual cyclists' activity constantly monitored. A second solution, which was already mentioned before, would consist on working on a route choice model and then estimating the distribution of flow according to the OD matrices and the considered cycling mobility modal share according to the Transport household survey. Although the model could be calibrated with counts and be sufficiently accurate, it would be such a good solution as the previous one, since it just does not allow to track the evolution of cycling flow over time, it just provide an "static picture" of it.

RQ5. What are the mobility patterns of the different groups of cyclists –casual cyclists, bike messengers and BSS users–?

With the aim of providing an analysis of cyclists' routes and cycling flow as comprehensive as possible, we have included in this thesis the study of the three most important groups of cyclists I the city of Madrid: casual cyclists, bike messengers and BiciMAD (Madrid Bike Share System) users. As stated in the background section, the activity of the three groups have been increasing over the last decade in Madrid, partially encouraged by the pro-cycling policy measures, policies and infrastructure, implemented by the local government over the last years (Ayuntamiento de Madrid, 2015). Actually, regarding casual cyclists mobility, the evolution of the cycling modal share over the last years reveals this intense growth, going from the 0,22% in 2008 to 1,20% in 2015, according the data collected from different sources by Kisters, García, Rondinella, & Alduán (2016). Regarding bike messenger companies, while twenty years ago, only one of these companies was operating in the city of Madrid, now the figure has gone up to dozens, some of which are incorporating hundreds of new riders, such as *Deliveroo* or *Glovo*. Finally, in the case of BiciMAD, the activity has been increasing since it was launched, in mid-2014, comprising 1,560 bikes and 123 docking stations, to the present, when the system is operating with 2,028 bikes and 172 stations, and with approximately an average number of 8 thousand trips per day.

The results obtained from the different analyses confirms our initial hypothesis, and the three groups present some remarkable differences in their mobility patterns. Casual cyclists, bike messengers and BiciMAD users show very different patterns regarding average trip distances. While in the case of commuting casual cyclists' routes, the maximum concentration of trips correspond to distances between 3 and 6 km, and more than a 20% of trips correspond to journeys over 9 km length, when it comes to BiciMAD weekday users, the highest percentage of trips correspond to the ones that are approximately 2 km length, with just a 10% of trips over 5 km length, showing an abrupt decay which might be caused by the limits of the area currently covered by BiciMAD. Finally, regarding bike messengers, the highest concentration of their trips is between 1 and 2 km (revealing in a way what is the 'operational range' of distance of bike messengers' companies).

In addition, the analysis of the different groups of cyclists according cycling operating speeds, revealed also some remarkable findings. These results will be discussed later, in relation to a specific research question on this.

The main conclusion regarding the study of these three different groups of cyclists is that it is important to consider their coexistence as a whole group of urban cyclists as well as independently, as three different groups of cyclists. The comprehensive analysis of all of them is important in order to have an idea of the "whole picture" of cycling mobility and its distribution across the city, since, at the end of the day, the three of them use the cycling infrastructure implemented along certain streets, or are affected by general policies, as calming down the motor traffic in certain areas, for instance.

However, the analysis of the three groups independently is important, because they respond to a different profile of people, in most cases cycling with a different purpose and in consequence having also particular needs, and knowing about these needs is important to promote specific measures, policies or infrastructure that may result effective for each group. For instance, bike messengers, especially those delivering parcels from shopping mall areas to consumers' residences, could be benefit from measures that promote the implementation of charging stations, so that their bikes (and their navigation devices) can be charged while they are collecting and organizing the parcels. In the case of casual cyclists, the implementation of more parking points located in the areas with higher demand, or to implement other infrastructure close to or at facilities of some companies, in agreement with them, with the aim of promoting cycling mobility in the area where an important flow of commuting cyclists (or potential commuting cyclists) has been identified. Finally, the analysis of BiciMAD users' travel patterns may shed light on the kind of infrastructure that become more attractive to them, or to a certain group of their users (such as tourists) and in consequence try to support and channelize the flow of this group by implementing some of them strategically connecting the most important touristic areas, for instance.

RQ6. What is the impact that different urban conditions, cycling infrastructure or variables related to the journey or to the cyclists, have on cycling mobility? How all the factors affecting cyclists shape their mobility patterns?

As stated in the background section, cyclist behaviour is complex and not easily predictable because it is influenced by a diverse set of factors. The different analyses conducted in this thesis had shed light on the influence of some of them, and some conclusions can be drawn based on the study of cyclists' behaviour and routes, as well as based on the analysis of the cycling flow distribution across the urban-street network.

With regard to the influence of cycling infrastructure, we have performed two different analyses. The first one, described in Section 4.3.2, is the analysis of the cycling flow "captured" or "supported" by streets where cycling infrastructure has been implemented, in relation to the extension or the length such network segments have. This analysis basically measures the percentage of cycling flow "channelized" by streets with any kind of cycling infrastructure as well as by the streets where road bike lanes (Ciclocarriles) or segregated bike lanes (Vías ciclistas) have been implemented, allowing us to measure the impact of the two main types of cycling infrastructure existing in Madrid. The results, illustrated in the Figure 4.11, shows, for instance, that approximately the 35% of streets with a cycling flow over 150 cyclists per day correspond to streets where segregated bike lanes have been implemented, an important percentage considering the fact that only a 17.48% of the street network segments correspond to this cycling infrastructure. It also allows as to compare the "attractiveness" of this infrastructure to the one of road bike lanes (Ciclocarriles), which support approximately the

22% of the street segments with the same level of cycling flow (a 33% less that the segregated bike lanes), with the 11.74% of the street network segments corresponding to this cycling infrastructure (also around a 33% less that the segregated bike lanes). So in this case, we could conclude that both infrastructure have a similar impact in streets with the maximum level of cycling flow in the case of BiciMAD users. Referred to the controversy about "ciclocarriles" in Madrid, the results show that these infrastructures seem to be performing well, although it is important to keep in mind that this can be more accessible for BiciMAD electric bikes users.

This analysis can be an interesting tool to measure the real impact of the different cycling infrastructure implemented in cities, since it asses their efficiency and not only their effectiveness, which could also be evaluated in terms of number of daily routes supported per km of infrastructure, which at the same time can be easily traduced in economic terms.

The second analysis that we have carried out in relation to the impact of cycling infrastructure is related to the analysis of their influence in cyclists' operating speed and travel times, which will be discusses in relation to the next research question.

This thesis also reveal the important impact of other variables on cycling mobility patterns, such as age and gender. The question of gender was addressed in Section 5, when performing the analysis of casual cyclists' mobility, based on the sample collected through the *Huella Ciclista de Madrid* initiative. The dataset collected from BiciMAD did not contemplate information about gender, so we could not consider this variable in the analysis. The first striking output was the existing imbalance in cyclists regarding gender: the proportion of males and females in the *Huella Ciclista de Madrid* sample was 72%-28% respectively, although this figures correspond to the imbalance previously uncovered by the studies conducted as part of the Cycling Mobility Master Plan or *Plan Director de Movilidad Ciclista de Madrid* (Ayuntamiento de Madrid, 2008), with the aim of analysing the existing cycling demand (DOYMO, 2011; EUSA Sociología, 2011; Monzon de Cáceres et al., 2011). In any case, these results are not so striking if we consider the existing imbalance the use of bicycle according to gender at an international level, illustrated in Figure 3.5: "Women's share of total bike trips" (Pucher & Buehler, 2008), especially in the countries where there is not an important cycling culture. On the contrary, in the case of the countries with highest levels of cycling mobility, such as Denmark or The Netherlands, this imbalance is inexistent, so we can conclude that, in the case of Madrid and Spain in general, the existing imbalance will be hopefully reduced as cycling mobility continues to grow.

Different mobility patterns regarding average cycling speed and trip distance are also found when analysing cyclists' routes according to gender. As the analysis of cyclists' operating speeds and travel times described in section 6 reveals, the average cycling speed of females is 2.64 kph less that males' one in the case of streets with motor traffic, and 1.93 less in the case of streets without motor traffic, evidencing also the highest impact of traffic on females, who may feel less comfortable or more intimidated when riding close to cars. Regarding the trip distance, the average travel distance is 6.267 m and 4,535 m for males and females respectively, figures that evidence that males' average travel distance is a 32% greater than females'. In this sense, figure 5.6 illustrates females' dramatic drop after reaching 5,500m, presenting a more asymmetric curve than males.

Regarding the question of age, the analysis of BiciMAD users reveals an important concentration of users between 27-40 years old, especially when comparing the percentages with Madrid's total population. Users between 27 and 40 years old are approximately 50% of users, in the case of frequent users, and significantly more in the case of occasional users, at almost 65%. In the case of the sample obtained through the *Huella Ciclista de Madrid* initiative, the proportion of cyclists between 25 and 40 years is similar (55%), with a 31% of cyclists over 40 years.

According to the different analyses performed, factor age does not affect significantly cyclists' travel patterns in terms of average speed or travel distance. In the case of BiciMAD frequent users, average cycling speeds and average trip distances remain quite stable, with slighly higher speeds and shorter trips in the age group between 27 and 40 years old. Age seems to affect more occasional users in both speed and distance, with a drop in values as the age is increased. In the casual cyclists, the regression analysed carried out in Section 6 reveals a minimum impact of age as well, which is quantified by the elasticity -0.03 (a cyclist 10 years older than another cyclist showed an average speed of just -0.3 kph lower). The almost inexistence of cyclists over 60-year-old in both samples may also explain these insignificant differences. A sample covering elderly people (even if their representation among the cycling community is really low) would probably changes these results.

With regard to the purpose of the journey, the analysis carried out based on the sample obtained through the *Huella Ciclista de Madrid* initiative, evidenced clear different patterns in terms of average travel distance and cyclists' speed. Commuting/working trips reported an average distance of 5,889 m, which slightly greater than the distances that correspond to leisure (5,705 m), shopping (5,648 m) and study purpose (5,201 m), and clearly greater that the average distance reported by trips with errands purposes (4,231 m). However, sport trips average distance was significantly higher, with an average of 21,002 m. The analysis of average speed according to the purpose of the journey will be discusses in relation to the next research question.

RQ7. How do cycling mobility patterns evolve over time?

Until recently, the analysis of cycling mobility was based on conventional data sources that provided information of cycling mobility for a specific date and time, a static view that could only produce static analyses on whatever aspect to be explored. The recent availability of new data sources has opened the opportunity to perform more dynamic analyses, based on data with high temporal resolution, constantly updated. This fact allows us to study the evolution of cycling activity over the course of a day, or to identify the potential different patterns of cycling mobility in different periods of time or at different dates of the year.

One of the goals of this thesis was to perform a dynamic analysis of cycling mobility. In the case of casual cyclists and bike messengers, the effort was concentrated on producing a video visualization (attached to this thesis manuscript as complementary content) that illustrates simultaneously casual cyclists and bike messengers cycling flow over the course of a day, revealing the complementary peaks of activity, something that static maps or representations cannot communicate clearly enough.

In the case of the dynamic analysis of the cycling flow derived from BiciMAD activity, the rich sample allowed us to perform more analyses and better visualizations. We were able to explore the different dynamics of use that BiciMAD experiences over time and according to its different types of users. For instance, we could find out that during weekends and holidays, frequent users' trips are slightly longer than during the weekdays, and the average speed is somewhat lower than during the weekdays. Another remarkable difference was found when analysing frequent users' figures over the course of the day. The average speed of frequent users' trips during the morning peak hour is the highest, at 15.71 kph, which can be associated to the rush typical of commuting trips. The average speeds during the rest of the day are clearly lower, around 13.50 kph, before they once again rise after 10pm, and especially after 1am, something that could be explained by the quasi-absence of motor traffic, which means that cyclists most likely do not stop at every junction or traffic light, significantly reducing travel time.

Different patterns were also found when comparing weekday activity vs. weekend and holiday activity. Weekdays shows a clear morning peak hour that corresponds to commuting trips, and then a second peak in the afternoon and evening, which is earlier in the afternoon on Fridays. This is due to the fact that it is common to finish working early on Fridays in many companies or sectors. Weekends and Eastern days' activity perform in a similar way, with a reduced activity early in the morning and a continuous increase towards the afternoon and the evening. The night activity during in these cases after 1 AM is also remarkable, showing an important use of BiciMAD associated with nightlife during weekends and holidays, which is characteristic of the city of Madrid. The cycling activity at night maintain an important activity until 3h during weekends, when, despite the vivid nightlife of Madrid, other transport modes have already finished its service (at 1:30h in the case of the tube) or reduce it (in the case of many bus lines).

In addition, two maps illustrate BiciMAD average cycling flow in two different scenarios: on a working day and on a weekend day. Both maps are quite complementary and illustrate the different uses of the city street-network over time in terms of cycling flow, which can be used as a valuable tool when defining the increasingly-common different cycling policies and measures that many cities are adopting temporally for weekdays and weekends.

Finally, a video visualization was produced in order to show BiciMAD activity over the course of a day, reproducing every single trip in a clip aimed at illustrating the remarkable activity of a system which currently support over 8,000 trips per day.

The main conclusion regarding this analysis of cycling mobility over time, is that we are experimenting a paradigm shift towards more dynamic analyses and models. Models that calibrated thanks to the constant feed with real-time data coming from all kind of connected devices, will hopefully produce more accurate estimations for future scenarios, constituting a powerful tool for planning and policy making, as well as for the management of services such as BiciMAD.

RQ8. What are the factors that have a greater impact on cyclists' operating speeds and travel times?

In this thesis, cyclists' speeds have been analysed at two different levels. Firstly, cyclists' average speeds have been estimated for the three different groups of cyclists included in this research (casual cyclists, bike messengers and BiciMAD users). Secondly, based on the detailed examination of the thousands of GPS routes collected through the *Huella Ciclista de Madrid* initiative, different OLS regression models were conducted in order to analyse cyclists' speed according to the diverse local factors that affect cyclists along the different street segments of their journey, such as the slope, the existence –and type– of bike infrastructures, the average traffic speed or the distance to traffic lights or intersections.

The analysis of cycling operating speeds according to the different groups of cyclists revealed some remarkable findings. The first one is that, contrary to popular belief, BiciMAD users' speeds are not higher than casual cyclists' speeds, but slightly lower (14.29 vs.15.03 kph), although, when considering commuting trips both groups present very similar operating speeds (15.71 vs.75 kph). Although this finding may result surprising considering that all BiciMAD bikes are e-bikes and offers electric assistance, some BiciMAD users might not have the experience and familiarity of regular casual cyclists, so they ride at lower speeds. Actually, this could be the case especially considering that the volunteer cyclists joining the *Huella Ciclista de Madrid* initiative could correspond to a more compromised and experienced cyclist profile, related to the cycling associations that supported the initiative. In this case, is that bike messengers' speeds are clearly higher than casual cyclists' and BiciMAD users' one, with 19.60 kph and 19.70 kph when riding normal bikes and the increasingly common bullit bikes, respectively. The only exception for this group correspond to bike messengers using cargo trikes, in which case the average speed is 11.40 kph. Bike messengers' average speed is even higher than the one of casual cyclists considering sport as the purpose of the journey (15.87 kph), a fact that may not result unexpected if we take into account that the extension that we have covered with the *Huella Ciclista de Madrid* is the essentially Madrid municipal area and, in consequence, we are not including but an small sample of sportive cyclists activity, and most of them are mountain bikers (in the Casa de Campo park, for instance), rather than road sportive cyclists.

The analysis of cyclists' speed according to a wide range of local factors that affect cyclists along the different street segments of their journey, shed light on the influence of these factors on cyclists' speed by quantifying their specific impact. The factors having more influence on cyclists' speed proved to be gender (females' speed being 2.64 kph lower that males' in roads with traffic, and 1.93 less in the case of streets without motor traffic), the slope of the street, the presence of intersections and traffic lights along the streets and the existing average motor traffic speed. The purpose of the journey is also a key variable, with some particular purposes having a significant impact compared to the one considered by default in the models (working). Cyclists' speed when traveling for shopping, leisure or errands is lower and higher when sport is the purpose. The *Journey total duration* and the *Journey total elevation gain* have also a negative impact. Regarding the impact of the different types of cycling infrastructure on cyclists' speed, the models revealed that some of them significantly increased cyclists' speed, such as *Segregated* or *Non-segregated bike-lanes*, while others have a negative impact on it, such as Bike-lane on sidewalks. Although age has a negative influence, its impact is not so important. When it comes to the weather, average speeds decrease on cloudy days, and especially on rainy days.

RQ9. Is cycling a competitive transport mode in terms of accessibility?

As we stated in the introduction section, we all agree that cycling is a sustainable transport mode, the most sustainable transport mode after walking and we also know about the different social, economic and environmental benefits of promoting cycling in cities. But, is cycling also a competitive transport mode? Very little studied have focussed on analysing how cycling can compete with other transport mode in terms of the accessibility that it provides.

Beside the estimation of the specific impact of these factors, the models conducted were useful for another purpose.

In addition to the estimation of a wide range of factors on cyclists' speeds, the previously mentioned OLS regression models were useful for estimating cyclists travel times. Although the different models showed modest R-squared values when predicting cyclists' speed at a particular route segment, they performed quite well when predicting cyclists' travel times for an entire route, so average travel times can be estimated with certain accuracy. Based on this estimated travel times, it was possible to conduct a comparative analysis of accessibility, evaluating competitiveness between different transport modes: cycling (including BiciMAD-Madrid Bike Share System-), walking, private car and public transport.

The results of this comparative analysis evidenced that cycling is the most competitive transport mode for what we could consider "small-medium distances" (under 21 minutes in length for Madrid), a relevant finding not only for casual cycling mobility, but also for bike-driven parcel delivery services, since bike-messenger performance is even greater than casual cyclists'. The same analysis also evidence the limited accessibility provided by BiciMAD (Madrid Bike-Share System) essentially due to its current level of implementation, covering only the core of the city of Madrid.

Based on these results, this thesis aims at raising awareness of cycling, not only as an environmentally-sustainable transport mode, but also as the most efficient mode for an important range of distances.

7.1.2 General conclusions and considerations regarding the research as a whole

1. *With regard to the main research objectives and in relation to other similar studies.*

   As stated in the Introduction section, the main research goal of this thesis was, essentially, to study urban cycling flow. However, although this goal condenses the main intention, it does not reveal any motivational purpose or aim behind it. The real purposes were better unfolded when formulating the general objectives: to visualise and analyse cyclists' routes and cyclists' mobility patterns according to a wide range of variables, to analyse the distribution of cycling flow across the urban street-network, and to study also the general mobility patterns of the "cycling city" and their evolution over time. The thesis also aimed to analyse cyclists' operating speeds, to estimate and model cycling travel times and then, to perform a comparative analysis of cycling accessibility in relation to other transport modes.

   Although many of the research questions addressed can and should be further explored, as we will refer to in the Future research lines section, we consider that the main objectives of this thesis have been essentially achieved:

   + This thesis has illustrated, for the first time, cycling flow in the city of Madrid, and, as far as we know, it is the first study that performs a comprehensive analysis including casual cyclists but also bike messengers and Public Bike-Share System users (from BiciMAD), initially out of the scope of the study. Other similar studies, such as the ones previously performed in San Francisco, California (Hood et al., 2011), and Austin, Texas (J. G. Hudson, Duthie, Rathod, Larsen, & Meyer, 2012) focussed just on regular cyclists, and so it did a similar initiative running during the same period in the Netherlands, Bike Print (2014).

+ The initiative *Huella Ciclista de Madrid*, and the development of its core, the digital platform, has played a crucial role, serving as a collector of cyclists' routes, since online maps were not only conceived as visualization tools (which allowed a dynamic and active exploration of cyclists' routes, represented according to the purpose of the journey, for instance, and displaying information associated to such routes), but also as platforms to collect data from volunteers. These platforms respond to a paradigm shift in the way data is being collected nowadays: New platforms or apps do not simply ask for data (as ordinary surveys do); they offer something in exchange, they provide a service and, if possible, raise awareness of the motivation behind any initiative. If volunteers think that something makes sense and is useful for them, they will find it worthy and meaningful to participate, even if anything else –material or economic incentives– is provided in exchange. From my personal point of view, this is one of the most important and useful conclusions I get from this thesis.

  This approach is also different from the one that other similar initiatives have. For instance, the studies performed in San Francisco, California (Hood et al., 2011), and Austin, Texas (J. G. Hudson, Duthie, Rathod, Larsen, & Meyer, 2012) do not include a digital platform or online maps illustrating the global cyclists' footprint obtained, and, although Bike Print (2014) in the Netherlands displays online maps in a website, the initiative do not offer the possibility of engaging bike-messengers or Public-Bike Share users, excluding an important amount of cyclists.

+ In addition to work on these visualization tools, this thesis analyses cyclists' routes and cyclists' mobility patterns according to a wide range of variables related to urban and street-network conditions, as well as to personal conditions of variables related to the journey (such as the purpose of the journey). Especially significant is the contribution it does (for the first time, as far as we know it according to existing literature) when analysing cyclists' average speeds and travel times according to the impact of a wide range of factors (slope, the existence of different types of cycling infrastructure, motor traffic speed, traffic lights or street-junction density, etc.), with a level of accuracy (considering the GPS data) and comprehensiveness that had not been carried out yet, as far as we know from the literature reviewed.

+ This thesis also aimed at analysing the cycling city, not only cyclists' mobility. In this sense, it has explored the distribution of cycling flow across the city network, studying also the level of use of the existing cycling infrastructure, and proposing new ways to measure it through indicators and graphs that could be useful when monitoring cycling flow over time and therefore when evaluating the impact of different measures or infrastructure.

+ This thesis has explored both cyclists' routes and the "cycling city" in a dynamic way, taking advantage of the temporal dimension of time and the rich temporal resolution obtained in some cases. As a result of this, different maps and video-visualizations represent both cyclists' routes and the changing cycling city activity over time.

+ Based on the estimation of cyclist average speeds and travel times, this thesis has performed an analysis of accessibility and a comparative analysis of competitiveness between different transport modes, leading to an important message: cycling is not only a sustainable mode of transport, but also a very competitive one when considering short-medium distances. As far as we know, it is the first time different modes of transport travel times are compared to cyclists mobility real travel times obtained both from casual cyclists and bike-share users.

+ Finally, this thesis provides the tools to predict and model cycling travel times and cycling accessibility for future scenarios, derived from the implementation of specific policies or the construction of particular infrastructure, which can be considered and very useful tool for policy makers and urban transport planners.

In addition to this general conclusion, at this point, it is worthy to provide a number of general considerations and conclusions regarding the whole research conducted.

2. *On the complex nature of cycling mobility.*

Cycling is trendy. Not only in cities, but also in academia. It is difficult to know the reasons why cycling has become so popular within the research community but, whatever they are, it is a fact that cycling mobility is being currently analysed from multiple perspectives by researchers from many different disciplines: from phycologists to transport engineers, from social-scientists, urban planners or geographers, to data scientists or computer developers.

This relevant multidisciplinary approach reflects the complex nature of cycling mobility, and the fact that the research production on cycling mobility has grown exponentially evidences the extraordinary interests of this field of research.

Concerning this thesis, this complexity drove this research through a journey which involved a wide range of interests and topics, from social participation or collaborative initiatives, to digital platforms, online maps and new data sources. This thesis has been also a vehicle for me, which allowed me to explore different visualization, analysis and modelling techniques. In this sense, my interests have not been just focused on the topic (I did not aim to become an expert on cycling mobility), but also on the theoretical frameworks that I had to learn.

3. *On new data sources and the research paradigm shift towards dynamic analyses and models.*

In some way, this thesis is our first approach to a dynamic analysis of cycling mobility. The main conclusion is that this is just the beginning of a new research perspective, a paradigm shift fuelled by the ongoing revolution of Big Data. Institutions and companies are already aware of the enormous value of the data they are producing and hopefully will make it more accessible to researchers, who are already working on new dynamic transport models and dynamic analysis of accessibility, considering the different travel times of the diverse modes of transport over the course of a day. Therefore, more accurate models will soon come out, better calibrated thanks to the constant feed with real-time data coming from all kind of connected devices which will allow to produce not only long-term but short-term predictions, influencing the way people move around almost in real time. Finally, I'd like to underline the potentiality of using revealed preference methods, and its complementarity to declared preference ones, much more expensive.

4. *On the end of the transport mode classification as we know it*

Urban mobility is undergoing a rapid and intense revolution in many cities, with the emergence and recent adoption of new vehicles, electric-vehicles in most cases. This thesis analyses cycling mobility considering four different types of bicycles: regular bicycles, in the case of casual cyclists, *bullit-cargo bikes* and *cargo tricycles* integrating electric motors, in the case of bike-messengers, and *pedelecs* (or *pedal electric cycle*s), in the case of BiciMAD users. Although the majority of cyclists use one of these four different types of bicycles, this classification might be already obsolete. Dockless Bike Share is emerging in many cities, including Madrid, powerful E-bikes are becoming increasingly common, resulting in vehicles closer to electric mopeds than to bicycles. Also, electric mopeds are becoming widespread, with the emergence of electric scooter sharing services in many cities, including Madrid.

In addition, this thesis also performs a comparative analysis of accessibility between different transport modes, considering private cars, public transport (train, bus, underground and tramway), bicycles, bicycle sharing systems and pedestrian mobility. Again, this analysis might be soon obsolete, since a realistic comparative analysis of transport competitiveness will have to consider the emergent car-sharing services, or carpooling initiatives, or other peer-to-peer ridesharing companies.

5. *On the specific potential applications of this thesis, beyond the academic context.*

This research conducted in this thesis can be of interest for a number of different applications, beyond the academic context. First, it can be a tool for mobility planning and decision making. The analyses conducted contribute to a better understanding of cycling mobility. The estimation of the distribution of cycling flow across the city network can be –and should be– considered in order to analyse the level of use certain infrastructure, or the impact of a specific policy, and therefore assess their efficiency.

Second, the models developed in this thesis can also be applied to simulate different future mobility scenarios. They can predict the impact of certain measures or infrastructure on cyclists' operating speeds and travel times, and therefore estimate future accessibility scenarios, which could be included in comparative analyses of competitiveness between different transport modes, as it has already been done for the current scenario in Madrid.

Third, the dynamic analysis of certain cycling mobility patters and their evolution over time can be useful when promoting policies or measures for specific periods of time, something that has become a trend in many cities. For instance, closing certain streets to motor traffic, in order to promote pedestrian or cycling mobility during weekends, Sundays, or specific holidays. In addition, analysing cycling mobility over the course of the day and according to the different types of users provides important information in terms of the use of the system and the distribution of cycling flow during potential peak hours; for instance, this is crucial for the adoption of specific measures for these intervals of time at specific locations.

Finally, the analysis of cyclists' operating speeds and the derived analysis of competitiveness between transports modes carried out in this thesis, can be also applied to raise awareness of cycling, not just as a sustainable transport mode but also as a competitive one, for short and medium – distance trips.

6. *On building bridges between academia and planning authorities, institutions and practitioners.*

An enormous effort is being done in order to foster cycling mobility as a sustainable mode of transport, from institutions and planning authorities, to academia, involving an important amount of human and economic resources. However, although the work developed by the academia and the institutions should be close related, unfortunately, in many cases they follow separate and parallel paths. In consequence, on the one hand, it is common to find practices that do not consider the latest research advances, and continues to provide solutions based on obsolete methodologies or data. And on the other hand, it is also common to find research explorations that do not take into considerations the real needs and problems of cities in their effort of defining policies and planning infrastructure.

This research aims at building one of those necessary bridges between academia and practice, providing a contribution to the existing research on cycling mobility as well as at bringing new methodologies and tools for urban planners and decision makers.

7.2 Limitations of this thesis and future research lines

As previously stated, although we consider that the main objectives of this thesis have been essentially achieved, many of the research questions addressed can and should be further explored. The research presents some limitations and, in addition, during these years, we found new lines of research of our interest, related to the ones that we already were studying, but that we considered were out of the scope of this thesis. These limitations and future research lines are listed and briefly described next.

First, we would like to perform a dynamic analysis of accessibility focussed on BiciMAD, the Madrid Bike Share System. The analysis of accessibility carried out in the context of this thesis was a first step, and its real aim was to explore and show one specific application of the research focussed on estimating cyclists' speeds and travel times. The analysis should not consider just one point (as we did in this thesis with the centre of all the isochrones calculated and then compared), but a number of origins and destinations covering the whole urban area in which BiciMAD is operating. This analysis of accessibility would be dynamic in the sense that will consider the different value of certain variables over time, such as travel times or the different levels of availability of bicycle at the stations in origin as well as the availability of free docks at the destination-stations.

A second analysis to perform could be a comparative - dynamic analysis of accessibility, focussed on studying competitiveness between transport modes at different moments (over the course of a day, comparing weekdays and weekends, considering holidays, etc.). The comparative analysis of accessibility carried out in this thesis is limited to an specific moment (8:00h of a working day), but the availability of travel-time data at different moments of the day for other transport modes at the same location (considering Madrid still as the case study) would make this possible.

Third, a future research could be conducted with the aim of developing a cycling route-choice model based on the thousands of GPS routes collected by the *Huella Ciclista de Madrid* initiative, as well as on the GPS routes registered by BiciMAD. The research based on the first sample, obtained from casual cyclists and bike messengers, could be particularly useful, given the fact that the routes collected are just a sample of all the cycling routes that daily take place in Madrid. This was a limitation that did not allowed to estimate the distribution of cycling flow across the city, as we did in the case of BiciMAD, thanks to the availability of the data that corresponded to all the routes supported by the system. This distribution of casual cyclists and bike messengers' flow could be estimated by applying the route-choice model developed based on the data sample, and considering and estimation of the existing cycling demand between according to an origin-destination matrix.

Fourth, the values of cycling flow distribution across the urban street-network estimated in this thesis could be the base for further research focussed on the analysis of the factors that have an important impact on cyclists' safety. As previously stated, the geolocation of cyclists' accidents is nowadays commonly registered in urban areas, and the analysis of these geo-located accidents in relation to the distribution of cycling flow is crucial in order to understand what areas can be considered as unsafe. Unfortunately, some widely disseminated studies or reports identify "the worst cycling blackspots" just based on the amount and location of accidents (Beach, 2016), although it is evident that applying a principle of proportionality (the more cyclists, the more accidents, under similar circumstances) it is necessary in order to assess the real risk of accident. This analysis is important not only in order to improve cycling safety, but also in order to refute the mainstream idea that cycling is a dangerous mode of transport, when there are, at least in the case of Spain, evidences of the contrary idea (León, 2017) based on collected data of traffic flow and number of accidents for all modes of transport (Dirección General de Tráfico, 2015). In summary, the analysis of cycling flow may contribute to this discussion with important data that will allow to evaluate cycling safety and risks in a more objective way.

Fifth, a new research line should be launched as a response to what we considered previously regarding *the end of the transport mode classification as we know it*. The emergence and recent adoption of new systems (such as Dockless Public Bike-Share Systems) and vehicles, electric-vehicles in most cases (such as E-bikes or electric mopeds) as well as the emergence of electric scooter sharing services, car-sharing services, carpooling initiatives, or other peer-to-peer ridesharing companies, should be analysed and included in any analysis of accessibility and competitiveness between transport modes.

Finally, it is important to highlight an important limitation of this research: the analysis of casual cyclists and bike messengers' mobility has been carried out based on a limited sample of 6,022 cycle routes, resulting in 48,122 km of tracks uploaded by 328 volunteer cyclists. We aim at re-launching the *Huella Ciclista de Madrid* in the near future, hopefully with the support of institutions or planning authorities, so we will be able of increasing the sample and conducting a constant monitorization of casual cyclists and bike messenger's mobility. Based on this extended sample, we could identify the most important urban streets in terms of cycling flow, not only including BiciMAD users, but the whole cyclists' community. In addition, based on this extended sample, we could conduct more robust analyses and build more accurate and dynamic models, which would be powerful tools for developing a better planning and policy making.

8 Appendices

8.1 List of publications, conference presentations and awards related to the thesis.

8.1.1 Publications

The results of this thesis have been already published or are being published in different Scientific Journals. A complete list of the academic papers is provided next.

1. ***Big Data and cycling*** (2015).
   TTRV Transport Reviews, Taylor & Francis. JCR Impact factor 3.188, Q1.
   Authors: Romanillos, Gustavo; Zaltz-Austwick, Martin; Ettema, Dick; De Kruijf, Joost.
   DOI: 10.1080/01441647.2015.1084067. Available at:
   http://dx.doi.org/10.1080/01441647.2015.1084067

1. ***Madrid cycle track: Visualizing the cyclable city*** (2016). Journal of Maps, Taylor & Francis. JCR Impact factor: 1.545, Q2. Authors: Gustavo Romanillos & Martin Zaltz Austwick. DOI: 10.1080/17445647.2015.1088901. Available at: http://dx.doi.org/10.1080/17445647.2015.1088901

2. ***The pulse of the cycling city: visualising Madrid bike share system GPS routes and cycling flow*** (2018) Authors: Romanillos, Gustavo; Zaltz-Austwick, Martin; Moya-Gomez, Borja and Patxi. J. Lamíquiz Daudén. Journal of Maps, Taylor & Francis. JCR Impact factor: 1.545, Q2. Available at: https://doi.org/10.1080/17445647.2018.1438932

3. ***Cyclists do better. Analysing urban cycling operating speeds, accessibility and competitiveness in relation to other transport modes***. Paper submitted to The International Journal of Sustainable Transportation in in October 2017, accepted, and currently under review. Authors: Gustavo Romanillos & Javier Gutiérrez.

Part of the research has been also published in non-academic journals:

4. *Madrid Cyclist Track (2015).* UrbanNext, Actar Publishers. ISSN 2575-5374 . Available at: https://urbannext.net/madridcyclisttrack/

In addition, the next book chapter will be published soon:

5. *Nuevos datos para una nueva cartografía de la movilidad ciclista en la ciudad.* (2018). Authors: Gustavo Romanillos and Juan Carlos García-Palomares. Colección de Desarrollo Territorial. Publicaciones de la Universidad de Valencia sobre las Jornadas de Movilidad Sostenible.

Finally, part of the research has been also published as Conference Proceedings:

6. *Analysing and Mapping the Cyclable City – A GPS-based Analysis of the Real and Potential Cyclability of Madrid* (2014). Digital Landscape Architecture 2014. Peer Reviewed Proceedings of DLA 2014 International Conference at ETH Zürich. Authors: Gustavo Romanillos and Javier Gutiérrez Puebla. Available at: http://dla2014.ethz.ch/talk_pdfs/DLA_2014_7_Romanillos.pdf

7. *La huella digital de BiciMAD: visualización y análisis de rutas GPS y flujo ciclista de la bicicleta pública en Madrid (2018).* XVIII Congreso Nacional de Tecnologías de la Información Geográfica. Valencia (Spain). Authors: Gustavo Romanillos, Javier Gutiérrez y Borja Moya-Gómez. Available at: https://congresos.adeituv.es/tig2018/ficha.es.html

8.1.2 Conference presentations

The research conducted throughout this thesis has been presented in the following conferences:

1. NECTAR XIV International Conference: Transport in a networked society (2017)
   Presentation of research: "Cyclists do better. Analysing urban cycling operating speeds, accessibility and competitiveness in relation to other transport modes"
   Authors: Gustavo Romanillos & Javier Gutiérrez

2. AAG Annual Meeting. Association of American Geographers (2015). Chicago, Illinois, USA.
   Presentation of research: Simulating Rush Hour Bicycle Traffic in Madrid.
   Authors: Martin Austwick and Gustavo Romanillos
   http://meridian.aag.org/callforpapers/program/AbstractDetail.cfm?AbstractID=65428

3. CASA Seminars. Centre for Advance Spatial Analysis (CASA), University College of London.
   Seminar: "Visualising the cyclable city" (2014) 1h.
   Authors: Gustavo Romanillos

4. Digital Landscape Architecture International Conference (2014). ETH Zürich, Switzerland.
   Presentation of research: "Analysing and mapping the cyclable city. A GPS-based analysis of the real and potential bicycle use in Madrid"
   Authors: Gustavo Romanillos
   Available at: http://dla2014.ethz.ch/talk_pdfs/DLA_2014_7_Romanillos.pdf

5. 6th CITTA Conference 'Responsive Transports for Smart Mobility' (2013). Coimbra, Portugal
   Presentation of research: "Optimizing the cyclable city. Building a bikeway network design model based on the analysis of the cyclability of Madrid"
   Authors: Gustavo Romanillos and Javier Gutiérrez

6. NECTAR XII International Conference (2013). Sao Miguel, Azores, Portugal
   Presentation of research: 'Cyclist network design model based on the analysis of the cyclability of the network and Potential Cyclist Flow'
   Authors: Gustavo Romanillos and Javier Gutiérrez

7. 3th Annual Conference on Human Geography Research (2013). Complutense University of Madrid, Spain
   Presentation of research: Towards the cyclable city.
   Authors: Gustavo Romanillos

8.1.3 Awards

The research conducted throughout this thesis has received the following awards:

1. Best Visualisation Prize. Festival for Digital Health 2014. University College of London.
   Report available at: http://www.fdh.ucl.ac.uk/wp-content/uploads/2014/08/UCLFDH-Eval.pdf

2. Best Map Prize. Digital Landscape Architecture International Conference 2014. ETH Zürich

Report available at: http://dla2014.ethz.ch/awards/

3. Best Map Prize. Winner of the Map Gallery 2014. ESRI Spain National Conference 2014. Madrid
Report available at: http://www.esri.es/los-mejores-de-ce13/

8.2 Authorizations of co-authors to the publication of papers

This thesis comprises excerpts of different papers that I have written in collaboration with other authors. I have received their authorisation to publish them in this thesis dissertation, and the documents that prove this consent are provided next.

Profesor Gustavo Romanillos Arroyo
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21-March-2018

Dear Professor Dick Ettema,

I am completing a doctoral dissertation at the Universidad Complutense de Madrid entitled ***"The digital footprint of the cycling city. GPS cycle routes visualization and analysis"***. I would like to have your permission to reprint in my dissertation excerpts from the paper "Big Data and cycling", published in 2016 in the journal Transport Reviews, 36(1), pp.114–133, as one of the authors of the paper, written together with Martin Zaltz-Austwick, Joost De Kruijf and myself.

My dissertation will be produced electronically and made available through the Universidad Complutense Library and its publication partners. I am requesting permission to include the excerpts in current and future revisions and editions of my dissertation, and to grant others the right to reproduce my entire dissertation, for educational, non-commercial purposes. These rights will in no way limit republication of the material in any other form by you or others authorized by you.

Your signing will verify that you own the copyright to the above material.

If this meets with your approval, please sign this letter below and return it to me in an enclosed return envelope, and also digitally via email. Thank you very much for your attention to this matter.

Sincerely,

Gustavo Romanillos Arroyo

PERMISSION GRANTED FOR THE USE REQUESTED ABOVE:

Professor Dick Ettema

Date: 22 - 3 - 2018

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21-March-2018

Dear Dr. Martin Zaltz-Austwick,

I am completing a doctoral dissertation at the Universidad Complutense de Madrid entitled “***The digital footprint of the cycling city. GPS cycle routes visualization and analysis***”. I would like to have your permission to reprint in my dissertation excerpts from the paper “Big Data and cycling”, published in 2016 in the journal Transport Reviews, 36(1), pp.114–133, as one of the authors of the paper, written together with Joost De Kruijf, Dick Ettema and myself.

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21-March-2018

Dear Borja Moya Gómez,

I am completing a doctoral dissertation at the Universidad Complutense de Madrid entitled ***"The digital footprint of the cycling city. GPS cycle routes visualization and analysis"***. I would like to have your permission to reprint in my dissertation excerpts from the paper "The pulse of the cycling city: visualising Madrid bike share system GPS routes and cycling flow", published in 2018 in Journal of Maps 14 (1), 34-43, as one of the authors of the paper, written together with Martin Zaltz-Austwick, Patxi J. Lamíquiz-Daudén and myself.

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21-March-2018

Dear Joost De Kruijf,

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21-March-2018

Dear Professor Javier Gutiérrez Puebla,

I am completing a doctoral dissertation at the Universidad Complutense de Madrid entitled "***The digital footprint of the cycling city. GPS cycle routes visualization and analysis***". I would like to have your permission to reprint in my dissertation excerpts from the paper "Cyclists do better. Analysing urban cycling operating speeds and accessibility", submitted to The *International Journal of Sustainable Transportation* in in October 2017 (and currently under review), as one of the authors of the paper, written together with me.

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Date: 22 de Marzo de 2018

9 References

Albergotti, R. (2014). Strava, Popular With Cyclists and Runners, Wants to Sell Its Data to Urban Planners. *Wall Street Journal*. Retrieved from http://blogs.wsj.com/digits/2014/05/07/strava-popular-with-cyclists-and-runners-wants-to-sell-its-data-to-urban-planners/

Anaya, E., & Castro, A. (2011). Balance general de la bicicleta pública en España. In *3as Jornadas de la Bicicleta Pública Santander*. Santander. Retrieved from https://s3.amazonaws.com/academia.edu.documents/31086906/1-EsterAnaya-AlbertoCastro.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1513012631&Signature=szVlhgSqFq4%2Fv5UhqNM7IgHXgjc%3D&response-content-disposition=inline%3B filename%3DBalance_General_de_

Asociación Pedalibre. (2007). *Estadística Bicis Madrid*.

Ayuntamiento de Madrid. (2008). Plan Director de Movilidad Ciclista (PDMC) de Madrid. Madrid.

Ayuntamiento de Madrid. (2015). *Informe del Estado de la Movilidad de la Ciudad de Madrid 2014*. Madrid.

Ayuntamiento de Madrid. (2016). *INFORME CONTESTACIÓN A LAS SUGERENCIAS Y APORTACIONES PRESENTADAS AL DOCUMENTO DE "REVISIÓN Y ACTUALIZACIÓN DEL PLAN DIRECTOR DE MOVILIDAD CICLISTA."* Madrid. Retrieved from http://www.madrid.es/UnidadesDescentralizadas/UDCMovilidadTransportes/BICI/OficinaBici/Plan_Director_Movilidad_Ciclista/Informe_contestacion_sugerenciasPDMC08+.pdf

Balshone, B. L., Deering, P. L., & McCarl, B. D. (1975). *Bicycle transit: its planning and design*. Praeger Publishers.

Barnes, G., & Krizek, K. (2005). Estimating Bicycling Demand. *Transportation Research Record*, *1939*(1), 45–51. https://doi.org/10.3141/1939-06

Bauman, A., Titze, S., Rissel, C., & Oja, P. (2011). Changing gears: bicycling as the panacea for physical inactivity? British Association of Sport and Excercise Medicine.

Beecham, R., & Wood, J. (2014). Characterising group-cycling journeys using interactive graphics. *Transportation Research Part C: Emerging Technologies*, 1–13. https://doi.org/10.1016/j.trc.2014.03.007

Ben-aiuva, M., & Morikawa, T. (1990). Estimation of switching models from revelaed preferences and stated intentions. *Transport Research A*, *24*(6), 485–495.

Bernmark, E., Wiktorin, C., Svartengren, M., Lewné, M., & Aberg, S. (2006). Bicycle messengers: energy expenditure and exposure to air pollution. *Ergonomics*, *49*(14), 1486–95. https://doi.org/10.1080/00140130600708206

Black, J. A., Paez, A., & Suthanaya, P. A. (2002). Sustainable urban transportation: performance indicators and some analytical approaches. *Journal of Urban Planning and Development*, *128*(4), 184–209.

Blanchar, C. (2017, June 4). La bici se acelera en Barcelona. *El País*. Retrieved from https://elpais.com/ccaa/2017/06/03/catalunya/1496505839_193912.html

Bohannon, R. W. (1997). Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. *Age and Ageing*, *26*(1), 15–19. https://doi.org/10.1093/ageing/26.1.15

Borgnat, P., Robardet, C., Abry, P., Flandrin, P., Rouquier, J.-B., & Tremblay, N. (2013). A Dynamical Network View of Lyon ' s V ´ elo ' v Shared Bicycle System. *Dynamics On and Of Complex*

Networks, Volume 2, 267–284.

Borgnat, P., Robardet, C., Rouquier, J.-B., Abry, P., Fleury, E., & Flandrin, P. (2011). Shared bicycles in a city: A signal processing and data analysis perspective. *Advances in Complex Systems*, *14*(3), 1–24. Retrieved from http://www.worldscientific.com/doi/abs/10.1142/S0219525911002950

Börjesson, M., & Eliasson, J. (2012). *The Benefits of Cycling: Viewing Cyclists as Travellers rather than Non-motorists*. *Cycling and Sustainability* (Vol. 1). Emerald Group Publishing Ltd. https://doi.org/10.1108/S2044-9941(2012)0000001012

Bradley, M. A., & Bovy, P. H. . (1984). A stated preference analysis of bicyclist route choice. *Planning and Transport Research and Computation*.

Bravo, P. (2016, June 11). ¿Por qué Madrid no quiere carril bici? *El Diario*. Retrieved from http://www.eldiario.es/desde-mi-bici/Madrid-quiere-tener-carril-bici_6_524657537.html

Bricka, S., Sen, S., Paleti, R., & Bhat, C. (2012). An analysis of the factors influencing differences in survey-reported and GPS-recorded trips. *Transportation Research Part C*, *21*(1), 67–88. https://doi.org/10.1016/j.trc.2011.09.005

Broach, J., Dill, J., & Gliebe, J. (2011). Bicycle Route Choice Model Developed from Revealed-Preference GPS Data. In *Transportation Research Board 90th Annual Meeting*. Retrieved from http://trid.trb.org/view.aspx?id=1093304

Broach, J., Dill, J., & Gliebe, J. (2012). Where do cyclists ride? A route choice model developed with revealed preference GPS data. *Transportation Research Part A: Policy and Practice*, *46*(10), 1730–1740. https://doi.org/10.1016/j.tra.2012.07.005

Buehler, R., & Dill, J. (2015). Bikeway Networks: A Review of Effects on Cycling. *Transport Reviews*, *1647*(May). https://doi.org/10.1080/01441647.2015.1069908

Buehler, R., & Pucher, J. (2012). Walking and cycling in Western Europe and the United States: trends, policies, and lessons. *TR News*, (280).

Button, J. (1989). How to be Green. London: Hentury hutchinson.

Castillo-Manzano, J. I., López-Valpuesta, L., & Sánchez-Braza, A. (2016). Going a long way? On your bike! Comparing the distances for which public bicycle sharing system and private bicycles are used. *Applied Geography*, *71*, 95–105. https://doi.org/10.1016/j.apgeog.2016.04.003

Cervero, R., & Duncan, M. (2003). Walking, bicycling, and urban landscapes: evidence from the San Francisco Bay Area. *American Journal of Public Health*, *93*(9), 1478–1483.

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D: Transport and Environment*, *2*(3), 199–219. https://doi.org/10.1016/S1361-9209(97)00009-6

Charlton, B., Schwartz, M., Paul, M., Sall, E., & Hood, J. (2010). CycleTracks: a bicycle route choice data collection application for GPS-enabled smartphones. In *3rd Conference on Innovations in Travel Modeling, a Transportation Research Board Conference*.

Cherry, C. R. (2007). *Electric two-wheelers in China: analysis of environmental, safety, and mobility impacts*. Citeseer.

Cheshire, J., & O'Brien, O. (2013). Revealing and Informing Transport Behaviour from Bicycle Sharing Systems. In *The Geographic Information Systems Research UK (GISRUK)*. Retrieved from http://www.geos.ed.ac.uk/~gisteac/proceedingsonline/GISRUK2013/gisruk2013_submission_

31.pdf

Cintia, P., Pappalardo, L., & Pedreschi, D. (2013). “Engine Matters”: A First Large Scale Data Driven Study on Cyclists’ Performance. In *2013 IEEE 13th International Conference on Data Mining Workshops* (pp. 147–153). Ieee. https://doi.org/10.1109/ICDMW.2013.41

Clarke, A., & Steele, R. (2011). How Personal Fitness Data Can be Re-used by Smart Cities. In *Seventh International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)* (pp. 395–400). New South Wales, Australia.

Comstock, J. (2013). 7 fitness apps with 16 million or more downloads. *Mobi Health News*. Retrieved from http://mobihealthnews.com/24958/7-fitness-apps-with-16-million-or-more-downloads/

CONECTA. (2015). Fomento del uso de la bicicleta en Madrid. Madrid.

Consorcio Regional de Tranpsortes de la Comunidad de Madrid. (2014). *Encuesta sintética de Movilidad*. Madrid. Retrieved from http://www.crtm.es/media/519661/esm_2014.pdf

Consumer. (2014). The U.S. digital consumer report. *The U.S. Digital Consumer Report*.

Cooper, C. H. V. (2017). Using spatial network analysis to model pedal cycle flows, risk and mode choice. *Journal of Transport Geography*, *58*, 157–165. https://doi.org/10.1016/j.jtrangeo.2016.12.003

Criollo Preciado, C. R. (2012). *Spatial Network Analysis for Urban Cycling Networks*. Technische Universität München.

Dalumpines, R., & Scott, D. M. (2011). GIS-based map-matching: development and demonstration of a postprocessing map-matching algorithm for transportation research. *Advancing Geoinformation Science for a Changing World*, 101–120.

Demaio, P. (2007). What a year for the bike-sharing.

Demaio, P. (2009). Bike-sharing : History , Impacts , Models of Provision , and Future. *Journal of Public Transportation*, *12*(4), 41–56.

DeMaio, P., & Gifford, J. (2004). Will smart bikes succeed as public transportation in the United States? *Journal of Public Transportation*, *7*(2), 1.

DGT. (2016). Guía para usuarios de la bicicleta.pdf. Spanish Directorate-General of Traffic. Retrieved from http://www.dgt.es/Galerias/seguridad-vial/educacion-vial/recursos-didacticos/jovenes/Guia-Bicicleta-agosto-2016.pdf

Dill, J. (2009). Bicycling for transportation and health: the role of infrastructure. *Journal of Public Health Policy*, *30*(1), S95–S110.

Dill, J., & Carr, T. (2003). Bicycle Commuting and Facilities in Major U . S . Cities If You Build Them , Commuters Will Use Them. *Transport Research Records*, (3), 116–123.

Dill, J., & McNeil, N. (2013). Four types of cyclists? Examination of typology for better understanding of bicycling behavior and potential. *Transportation Research Record: Journal of the Transportation Research Board*, *2387*, 129–138.

Dill, J., & Voros, K. (2007). Factors affecting bicycling demand: initial survey findings from the Portland, Oregon, region. *Transportation Research Record: Journal of the Transportation Research Board*, (2031), 9–17.

Doherty, S. T., Noel, N., Gosselin, M.-L., Sirois, C., & Ueno, M. (2001). *Moving beyond observed outcomes: integrating global positioning systems and interactive computer-based travel behavior surveys*. *Transportation Research Board*.

DOYMO. (2011). *Estudio de seguimiento de impacto de la implantación del PDMC: Eje Prado - Recoletos - Castellana.*

Ducret, R., & Delaître, L. (2013). Parcel delivery and urban logistics-changes in urban courier, express and parcel services: the French case. In *13th World Conference on Transport Research, July 15-18, 2013-Rio de Janeiro, Brazil*.

Ellison, R., & Greaves, S. (2011). Travel time competitiveness of cycling in Sydney, Australia. *Transportation Research Record: Journal of the Transportation Research Board*, (2247), 99–108.

Elvik, R. (2009). The non-linearity of risk and the promotion of environmentally sustainable transport. *Accident Analysis & Prevention*, *41*(4), 849–855.

eMarketer. (2014). Smartphone Users Worldwide Will Total 1.75 Billion in 2014. *eMarketer*. Retrieved from http://www.emarketer.com/Article/Smartphone-Users-Worldwide-Will-Total-175-Billion-2014/1010536

Emond, C., Tang, W., & Handy, S. (2009). Explaining gender difference in bicycling behavior. *Transportation Research Record: Journal of the Transportation Research Board*, (2125), 16–25.

Endomondo. (2012). *Endomondon by the numbers*. Retrieved from http://blog.endomondo.com/2012/06/27/endomondo-by-the-numbers/

Endomondo. (2014). *Endomondo Fitness App Runs Past 20 Million Users and Reaches Profitability*. Retrieved from Endomondo Fitness App Runs Past 20 Million Users and Reaches Profitability

Etienne, C., & Latifa, O. (2012). Model-based count series clustering for Bike-sharing system usage mining , a case study with the Vélib ’ system of Paris . *Transportation Research-Part C*, *5*(3), 1–23.

Europa Press. (2006, May 22). Los madrileños pierden cada día más de un cuarto de hora buscando aparcamiento. *El Mundo*. Retrieved from http://www.elmundo.es/elmundo/2006/05/22/madrid/1148313020.html

European Commission. (2011). *Transport White Paper*. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0144&from=EN

European Commission. (2014). No Title. Retrieved from http://ec.europa.eu/enterprise/policies/satnav/galileo/index_en.htm

European DG MOVE. (2014). Special Eurobarometer 422a. “Quality of transport.” European Directorate-General for Mobility and Transport. https://doi.org/10.2832/783021

EUSA Sociología. (2011). *Estudio de seguimiento de la evolución de la movilidad ciclista en el ámbito de los ejes ciclistas de josé del Hierro y Hermanos García Noblejas.* Madrid.

Evans, B. (2013). *Mobile is eating the world*. Retrieved from http://ben-evans.com/benedictevans/2013/11/5/mobile-is-eating-the-world-autumn-2013-edition

Faghih-Imani, A., Eluru, N., El-Geneidy, A. M., Rabbat, M., & Haq, U. (2014). How land-use and urban form impact bicycle flows: evidence from the bicycle-sharing system (BIXI) in Montreal. *Journal of Transport Geography*, *41*, 306–314. https://doi.org/10.1016/j.jtrangeo.2014.01.013

Fincham, B. (2007). Bicycle messengers: Image, Identity and Community. In P. Horton, Dave; Rosen, Paul; Cox (Ed.), *Cycling and society* (pp. 179–196). Ashgate Publishing, Ltd.

Fishman, E. (2011). The impacts of public bicycle share schemes on transport choice.

Fishman, E., Washington, S., & Haworth, N. (2013). Bike Share: A Synthesis of the Literature. *Transport Reviews*, *33*(2), 148–165. https://doi.org/10.1080/01441647.2013.775612

Fleming, S. (2012a). *Cycle Space: Architecture & Urban Design in the Age of the Bicycle*. Rotterdam: NAi010 publishers.

Fleming, S. (2012b). Cycle Space: Architecture & Urban Design in the Age of the Bicycle.

FLOW Project. (2017). *Walking, Cycling and Congestion. 15 Quick Facts for Cities*. Retrieved from http://h2020-flow.eu/fileadmin/user_upload/Deliverables/15_quick_facts_eng_FINAL.pdf

Flurry Analytics. (2014). Health and Fitness Apps Finally Take Off, Fueled by Fitness Fanatics. Retrieved from http://www.flurry.com/blog/flurry-insights/health-and-fitness-apps-finally-take-fueled-fitness-fanatics#.VA2Zmfl_tik

Fritz, S., & Lusardi, M. (2009). Walking speed: the sixth vital sign. *Journal of Geriatric Physical Therapy*, *32*(2), 1–5. https://doi.org/10.1519/00139143-200932020-00002

Froehlich, J., Neumann, J., & Oliver, N. (2009). Sensing and Predicting the Pulse of the City through Shared Bicycling. In *Twenty-First International Joint Conference on Artificial Intelligence (IJCAI-09)* (pp. 1420–1426). Beijing, China: AAAI Press.

Future, U. (2014, August 8). Cycling Mode Share Data for 700 Cities. *City Clock Magazine*. Retrieved from http://www.cityclock.org/urban-cycling-mode-share/#prettyPhoto/0/

García-Palomares, J. C., Gutiérrez, J., & Latorre, M. (2012). Optimizing the location of stations in bike-sharing programs: A GIS approach. *Applied Geography*, *35*(1–2), 235–246. https://doi.org/10.1016/j.apgeog.2012.07.002

GESOP. (2015). *Informe de Resultados del Barómetro anual de la bicicleta en España*. Retrieved from http://www.mobipalma.mobi/wp-content/uploads/2017/06/BarómetroBicicletaEspaña2015.pdf

Givoni, M., & Banister, D. (2010). *Integrated Transport: from policy to practice*. Routledge.

Goodman, A., & Cheshire, J. (2014). Inequalities in the London bicycle sharing system revisited: impacts of extending the scheme to poorer areas but then doubling prices. *Journal of Transport Geography*. https://doi.org/10.1016/j.jtrangeo.2014.04.004

Guo, Y., Liu, P., Bai, L., Xu, C., & Chen, J. (2014). Red Light Running Behavior of Electric Bicycles at Signalized Intersections in China. *Transportation Research Record: Journal of the Transportation Research Board*, *2468*, 28–37. https://doi.org/10.3141/2468-04

Harkey, D. L., Reinfurt, D. W., & Knuiman, M. (1998). Development of the Bicycle Compatibility Index. *Transportation Research Record*, (98), 13–20.

Harvey, F. J., & Krizek, K. J. (2007). Commuter Bicyclist Behavior and Facility Disruption. *Transportation Research Board*. Retrieved from http://trid.trb.org/view.aspx?id=811576

Helbich, M., Böcker, L., & Dijst, M. (2014). Geographic heterogeneity in cycling under various weather conditions: Evidence from Greater Rotterdam. *Journal of Transport Geography*, *38*, 38–47. https://doi.org/10.1016/j.jtrangeo.2014.05.009

Hillier, B. (2007). *Space is the machine: a configurational theory of architecture*. Space Syntax.

Hillier, B., & Hanson, J. (1989). *The social logic of space*. https://doi.org/http://dx.doi.org/10.1017/CBO9780511597237

Hong, Z., Wei, Z., & Wei, L. (2006). Bicycle-Based Courier and Delivery Services in Beijing. *Transportation Research Board*, (80), 45–51.

Hood, J., Sall, E., & Charlton, B. (2011). A GPS-based bicycle route choice model for San Francisco, California. *Transportation Letters The International Journal of Transportation Research*, *3*(1), 63–75. https://doi.org/10.3328/TL.2011.03.01.63-75

Hopkinson, P., & Wardman, M. (1996). Evaluating the demand for new cycle facilities as divergent as. *Transport Policy*, *3*(4), 241–249.

Howard, J. (1987). *The Cyclist's Companion* (Rev Sub ed). Penguin Books.

Hudson, J. G., Duthie, J. C., Rathod, Y. K., Larsen, K. A., & Meyer, J. L. (2012). *Using Smartphones to Collect Bicycle Travel Data in Texas*. Retrieved from http://utcm.tamu.edu/publications/final_reports/Hudson_11-35-69.pdf

Hudson, J., Qu, T., & Turner, S. (2010). *Forecasting bicycle and pedestrian usage and research data colletion equipment* (Vol. 7).

Hudson, M. (1978). *The bicycle planning book*.

Jacobsen, P. (2003). Safety in numbers: more walkers and bicyclists, safe walking and biking. *Inj Prev*, *9*, 205–209.

Jennings, G. (2016). *Global outlook on Walking and Cycling 2016. Policies & realities from around the world*. Retrieved from https://europa.eu/capacity4dev/unep/document/global-outlook-walking-and-cycling-policies-realities-around-world

Jestico, B., Nelson, T., & Winters, M. (2016). Mapping ridership using crowdsourced cycling data. *Journal of Transport Geography*, *52*. https://doi.org/10.1016/j.jtrangeo.2016.03.006

Jin, S., Qu, X., Zhou, D., Xu, C., Ma, D., & Wang, D. (2015). Estimating cycleway capacity and bicycle equivalent unit for electric bicycles. *Transportation Research Part A: Policy and Practice*, *77*, 225–248. https://doi.org/10.1016/j.tra.2015.04.013

Jónasson, Á., Eiriksson, H., Eðvarðsson, I., Helgason, K., Sæmundsson, T., Sigurgeirsson, D. B., & Vilhjálmsson, H. H. (2013). *Optimizing expenditure on cycling roads using cyclists ' GPS data*.

Kaltenbrunner, A., Meza, R., Grivolla, J., Codina, J., & Banchs, R. (2010). Urban cycles and mobility patterns: Exploring and predicting trends in a bicycle-based public transport system. *Pervasive and Mobile Computing*, *6*(4), 455–466. https://doi.org/10.1016/j.pmcj.2010.07.002

Kassim, A., Pascoe, L., Ismail, K., El Halim, A., & El Halim, A. (2012). Vision-Based Analysis of Cyclists' Speed. In *Transportation Research Board 91st Annual Meeting*.

Khatri, R. (2015). *Modeling Route Choice of Utilitarian Bikeshare Users from GPS Data*. University of Tennessee. Retrieved from http://trace.tennessee.edu/cgi/viewcontent.cgi?article=4837&context=utk_gradthes

Kidder, J. L. (2008). Appropriating the city: space, theory, and bike messengers. *Theory and Society*, *38*(3), 307–328. https://doi.org/10.1007/s11186-008-9079-8

Kidder, J. L. (2011). *Urban flow: Bike messengers and the city* (First Edit). Ithaca, NY: ILR Press.

Kisters, C., García, M. M., Rondinella, G., & Alduán, A. S. (2016). *Revisión y Actualización del Plan Director de Movilidad Ciclista de Madrid*. Madrid. Retrieved from http://www.madrid.es/portales/munimadrid/es/Inicio/Movilidad-y-transportes/Oficina-de-la-bici/Revision-y-actualizacion-del-Plan-Director-de-Movilidad-Ciclista/Plan-Director-de-Movilidad-Ciclista-2008-Revision-y-actualizacion?vgnextfmt=default&vgnextoid=04

Krizek, K. J., Johnson, P. J., & Tilahun, N. (2005). Gender differences in bicycling behavior and facility preferences. *Research on Women's Issues in Transportation*, *2*, 31–40.

Kroes, E. P., & Sheldon, R. J. (1988). Stated Preference methods. An introduction. *Journal of Transport, Economics and Policy*, *22*(1), 11–25.

Kumar, S., & Moore, K. B. (2002). The Evolution of Global Positioning System (GPS) Technology. *Journal of Science Education and Technology*, *11*(1).

Kurri, J., & Laakso, J. M. (2002). Parking policy measures and their effects in the Helsinki metropolitan area. *The Helsinki Metropolitan Area Publication Series C*, *18*.

Lamíquiz, P. J., & López-Domínguez, J. (2015). Effects of built environment on walking at the neighbourhood scale. A new role for street networks by modelling their configurational accessibility? *Transportation Research Part A: Policy and Practice*, *74*, 148–163. https://doi.org/10.1016/j.tra.2015.02.003

Landis, B., Vattikuti, V., & Brannick, M. (1997). Real-Time Human Perceptions: Toward a Bicycle Level of Service. *Transportation Research Record*, *1578*(1), 119–126. https://doi.org/10.3141/1578-15

Landis, B. W. (1996). Bicycle system performance measures. *ITE Journal*, *66*(2), 18–26.

Lantiga, I. (2017, October 11). BiciMad sobrepasará la M-30 y llegará por primera vez a Ciudad Lineal y Vallecas. *El Mundo*. Retrieved from http://www.elmundo.es/madrid/2017/10/17/59e5b88e46163f204c8b4639.html

Larsen, J., & El-Geneidy, A. (2011). A travel behavior analysis of urban cycling facilities in Montréal, Canada. *Transportation Research Part D: Transport and Environment*, *16*(2), 172–177. https://doi.org/10.1016/j.trd.2010.07.011

Larsen, K. A., Meyer, J., Duthie, J., & Khan, H. (2013). Mapping Bicycle Route GPS Data to a Street Network. In *Bicycle Urbanism Symposium*. Seattle: University of Washington.

LDA Consulting. (2012). *Capital bikeshare 2011 member survey report*. Washington DC.

Li, X., Ortiz, P. J., Browne, J., Franklin, D., Oliver, J. Y., Geyer, R., … Chong, F. T. (2010). Smartphone Evolution and Reuse: Establishing a More Sustainable Model. *2010 39th International Conference on Parallel Processing Workshops*, 476–484. https://doi.org/10.1109/ICPPW.2010.70

Lin, J. H., & Chou, T. C. (2012). A geo-aware and VRP-based public bicycle redistribution system. *International Journal of Vehicular Technology*, *2012*. https://doi.org/10.1155/2012/963427

Lin, S., He, M., Tan, Y., & He, M. (2008). Comparison Study on Operating Speeds of Electric Bicycles and Bicycles: Experience from Field Investigation in Kunming, China. *Transportation Research Record: Journal of the Transportation Research Board*, *1*(2048), pp 52-59. https://doi.org/10.3141/2048-07

Lindsey, G., Gorjestani, A., Hankey, S., Wang, X., & Chen, J. (2013). *Feasibility of Using GPS to Track Bicycle Lane Positioning*. Minneapolis, Minnesota (USA). Retrieved from http://purl.umn.edu/148996

Liu, X., Shen, L. D., & Ren, F. (1993). *Operational analysis of bicycle interchanges in Beijing, China*.

Luo, R., & Shen, Y. (2009). The Design and Implementation of Public Bike Information System Based on Google Maps. *2009 International Conference on Environmental Science and Information Application Technology*, 156–159. https://doi.org/10.1109/ESIAT.2009.298

Ma, L., Dill, J., & Mohr, C. (2014). The objective versus the perceived environment: what matters for bicycling? *Transportation*, *41*(6), 1135–1152. https://doi.org/10.1007/s11116-014-9520-y

Mach, P. (2014). What do 220,000,000,000 GPS data points look like? Retrieved from http://engineering.strava.com/global-heatmap/

MacMichael, S. (2014, September 22). Paris aims for 15 per cent modal share for cycling by 2020. *Road.cc*. Retrieved from http://road.cc/content/news/131015-paris-aims-15-cent-modal-share-cycling-2020

Macmillan, A., Connor, J., Witten, K., Kearns, R., Rees, D., & Woodward, A. (2014). The societal costs and benefits of commuter bicycling: Simulating the effects of specific policies using system dynamics modeling. *Environmental Health Perspectives*, *122*(4), 335–344. https://doi.org/10.1289/ehp.1307250

Madrid, E. B. por. (2017, September 11). ¿Hacia dónde se ampliará BiciMAD? Resultados de la encuesta. Retrieved from http://www.enbicipormadrid.es/2017/09/hacia-donde-se-ampliara-bicimad.html

Maes, J., & Vanelslander, T. (2012). The use of bicycle messengers in the logistics chain, concepts further revised. *Procedia-Social and Behavioral Sciences*, *39*, 409–423.

Map my fitness. (2014). Map my fitness. About us. Retrieved September 13, 2014, from http://about.mapmyfitness.com/about/company-history/

Map My Ride. (2014). Join over 20 million people getting fit on MapMyRide. Retrieved from http://www.mapmyride.com/routes/

Marqués, R., & Resumen, S. (2011). Sevilla: una experiencia exitosa de promoción de la movilidad en bicicleta en el Sur de Europa. *Hábitat Y Sociedad*, 107–130. Retrieved from http://acdc.sav.us.es/habitatysociedad/images/stories/N03/N03A06 Sevilla una promocion exitosa.pdf

Martens, K. (2004). The bicycle as a feedering mode: Experiences from three European countries. *Transportation Research Part D: Transport and Environment*, *9*(4), 281–294. https://doi.org/10.1016/j.trd.2004.02.005

Maus, J. (2014). ODOT embarks on “big data” project with purchase of Strava dataset. Retrieved from http://bikeportland.org/2014/05/01/odot-embarks-on-big-data-project-with-purchase-of-strava-dataset-105375

McCahil, C., & Garrick, N. W. (2008). The Applicability of Space Syntax to Bicycle Facility Planning. *Transportation Research Record: Journal of the Transportation Research Board*, *2074*(1), 46–51. https://doi.org/10.3141/2074-06

Meddin, R. (2011). The bike-sharing world: First days of summer 2011. *2011 [2012-12-12]. Http://bike-Sharing. Blogspot Com/search*.

Menghini, G., Carrasco, N., Axhausen, K. W., & Schüssler, N. (2010). Route choice of cyclists in Zurich. *Transportation Research Part A: Policy and Practice*, *44*(9), 754–765. https://doi.org/10.1016/j.tra.2010.07.008

Midgley, P. (2011). Bicycle-sharing schemes: enhancing sustainable mobility in urban areas. *United Nations, Department of Economic and Social Affairs*, 1–12.

Mitesh, S., Patel, M. D., MBA, M. S., & Hall, B. (2015). Wearable Devices as Facilitators, Not Drivers, of Health Behavior Change. *The Journal of the American Medical Association*, *13*(5). Retrieved from http://jama.jamanetwork.com/article.aspx?articleID=2089651

Monzón de Cáceres, A., del Val Melús, M. A., López Lambas, M. E., Lamíquiz Daudén, F. J., Montes García, M., & Fernández Heredia, Á. (2008). *Unibici Madrid. Estudio previo para la implantación de un sistema de préstamo de bicilcetas en la Ciudad Universitaria de Madrid*. Madrid. Retrieved from https://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwi_4bOQ1-DVAhXEuhoKHTs3AD0QFggoMAA&url=http%3A%2F%2Fwww.transyt.upm.es%2Findex.php%2Fes%2Fcomponent%2Fphocadownload%2Fcategory%2F1-unibici%3Fdownload%3D2%3Aunibici&usg=AFQjCNGGwJbXfX

Monzon de Cáceres, A., Rondinella, G., & Muñoz López, B. (2011). *Estudio de evaluación de la demanda, impacto social y sobre la movilidad urbana correspondiente al eje de la red básica de vías ciclistas de las calles Atocha - Mayor - Alcalá.*

Munkácsy, A. (2017). *User profiles and adoption attributes of innovative Bike-Sharing Systems: The case of BiciMAD (Madrid)*. Universidad Politécnica de Madrid. Retrieved from http://oa.upm.es/47849/

Munkácsy, A., & Monzón, A. (2017). Impacts of Smart Configuration in Pedelec-Sharing: Evidence from a Panel Survey in Madrid. *Journal of Advanced Transportation*, *2017*, 1–11. https://doi.org/10.1155/2017/4720627

Muñoz, B., Monzon, A., & Lois, D. (2013). Cycling Habits and Other Psychological Variables Affecting Commuting by Bicycle in Madrid, Spain. *Transportation Research Record: Journal of the Transportation Research Board*, *2382*, 1–9. https://doi.org/10.3141/2382-01

Muñoz, B., Monzon, A., & López, E. (2016). Transition to a cyclable city: Latent variables affecting bicycle commuting. *Transportation Research Part A: Policy and Practice*, *84*, 4–17. https://doi.org/10.1016/j.tra.2015.10.006

My fitness pal. (2014). Map My Ride. Retrieved September 14, 2014, from https://www.myfitnesspal.com/apps/show/184

Nelson, A., & Allen, D. (1997). If you build them, commuters will use them: association between bicycle facilities and bicycle commuting. *Transportation Research Record: Journal of the Transportation Research Board*, (1578), 79–83.

Newman, P., & Kenworthy, J. (1999). *Sustainability and cities: overcoming automobile dependence*. Island press.

Nielsen. (2014a). Hacking health: How consumers use smartphones and wearable tech to track their health. *Nielsen*. Retrieved from http://www.nielsen.com/us/en/insights/news/2014/hacking-health-how-consumers-use-smartphones-and-wearable-tech-to-track-their-health.html

Nielsen. (2014b). *Tech-styles: Are consumers really interested in wearing tech on their sleeves?* Retrieved from http://www.nielsen.com/us/en/insights/news/2014/tech-styles-are-consumers-really-interested-in-wearing-tech-on-their-sleeves.html

Noland, R. B., & Kunreuther, H. (1995). Short-run and long-run policies for increasing bicycle transportation for daily commuter trips. *Transport Policy*, *2*(1), 67–79. https://doi.org/10.1016/0967-070X(95)93248-W

Nordback, K., & Janson, B. (2010). Automated Bicycle Counts. *Transportation Research Record: Journal of the Transportation Research Board*, *2190*(1), 11–18. https://doi.org/10.3141/2190-02

O'Brien, O. (2010a). The bike share map. Retrieved from www.bikes.oobrien.com

O'Brien, O. (2010b). The bike share map.

O'Brien, O. (2013a). Bike Share Map. Retrieved from http://oobrien.com/bikesharemap/

O'Brien, O. (2013b). Bike Share Map.

O'Brien, O., Cheshire, J., & Batty, M. (2013). Mining bicycle sharing data for generating insights into sustainable transport systems. *Journal of Transport Geography*, *34*, 262–273. https://doi.org/10.1016/j.jtrangeo.2013.06.007

Ogilvie, D., Egan, M., Hamilton, V., & Petticrew, M. (2004). Promoting walking and cycling as an alternative to using cars: systematic review. *Bmj*, *329*(7469), 763.

Ohmori, N. (2005). GPS MOBILE PHONE-BASED ACTIVITY DIARY SURVEY. In *Eastern Asia Society for Transportation Studies* (Vol. 5, pp. 1104–1115).

Olafsson, A. S., Nielsen, T. S., & Carstensen, T. A. (2016). Cycling in multimodal transport behaviours: Exploring modality styles in the Danish population. *Journal of Transport Geography*, *52*, 123–130.

Oldenziel, R., & Albert de la Bruhèze, A. (2011). Contested Spaces: Bicycle Lanes in Urban Europe, 1900-1995. *Transfers*, *1*(2), 29–49. https://doi.org/10.3167/trans.2011.010203

Ortúzar, J. D. D., Iacobelli, A., & Valeze, C. (2000). Estimating demand for a cycle-way network. *Transportation Research Part A: Policy and Practice*, *34*(5), 353–373. https://doi.org/10.1016/S0965-8564(99)00040-3

Parkes, S. D., Marsden, G., Shaheen, S. A., & Cohen, A. P. (2013). Understanding the diffusion of public bikesharing systems: evidence from Europe and North America. *Journal of Transport Geography*, *31*, 94–103.

Peixoto, D. A. (2013). *Mining Trajectory Data*. Retrieved from http://courses.cecs.anu.edu.au/courses/CSPROJECTS/13S2/Reports/Alves_Peixoto_Douglas_Report.pdf

Portal de datos abiertos del Ayto. de Madrid. (2018). Portal de datos abiertos del Ayto. de Madrid. Retrieved from http://datos.madrid.es/portal/site/egob

Pucher, J. (1997). Bicycling boom in Germany: a revival engineered by public policy. *Transportation Quarterly*, *51*, 31–46.

Pucher, J., & Buehler, R. (2006). Why Canadians cycle more than Americans: A comparative analysis of bicycling trends and policies. *Transport Policy*, *13*(3), 265–279. https://doi.org/10.1016/j.tranpol.2005.11.001

Pucher, J., & Buehler, R. (2008). Making Cycling Irresistible: Lessons from The Netherlands, Denmark and Germany. *Transport Reviews*, *28*(4), 495–528. https://doi.org/10.1080/01441640701806612

Pucher, J., & Buehler, R. (2017). Cycling towards a more sustainable transport future. *Transport Reviews*, *37*(6), 689–694. https://doi.org/10.1080/01441647.2017.1340234

Pucher, J., Dill, J., & Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: an international review. *Preventive Medicine*, *50*, S106–S125.

Pucher, J., Garrard, J., & Greaves, S. (2011). Cycling down under: a comparative analysis of bicycling trends and policies in Sydney and Melbourne. *Journal of Transport Geography*, *19*(2), 332–345.

Rabl, A., & de Nazelle, A. (2012). Benefits of shift from car to active transport. *Transport Policy*, *19*(1), 121–131. https://doi.org/10.1016/j.tranpol.2011.09.008

Raford, N., Chiaradia, A., & Gil, J. (2007). *Space Syntax : The Role of Urban Form in Cyclist Route Choice in Central London*.

Rasmussen, T. K., Ingvardson, J. B., Halldórsdóttir, K., & Nielsen, O. A. (2013). Using wearable GPS devices in travel surveys : A case study in the Greater Copenhagen Area. In *Proceedings from th eAnnual Transport Conference at Aalborg University* (pp. 1–26). Aalborg, Denmark. Retrieved from http://www.trafikdage.dk/papers_2013/188_ThomasKjaerRasmussen.pdf

Raviv, T., Tzur, M., & Forma, I. A. (2013). Static repositioning in a bike-sharing system: models and solution approaches. *EURO Journal on Transportation and Logistics*, *2*(3), 187–229. https://doi.org/10.1007/s13676-012-0017-6

Reddy, S., Shilton, K., Denisov, G., Cenizal, C., Estrin, D., & Srivastava, M. (2010). Biketastic : Sensing and Mapping for Better Biking. *ACM Digital Library*, 1817–1820.

Reynolds, C. C. O., Harris, M. A., Teschke, K., Cripton, P. A., & Winters, M. (2009). The impact of transportation infrastructure on bicycling injuries and crashes: A review of the literature. *Environmental Health: A Global Access Science Source*, *8*(1). https://doi.org/10.1186/1476-069X-8-47

Rietveld, P. (2000). The accessibility of railway stations : the role of the bicycle in The Netherlands. *Transportation Research Part D*, *5*, 2–6.

Robinson, D. L. (2005). Safety in numbers in Australia: more walkers and bicyclists, safer walking and bicycling. *Health Promotion Journal of Australia*, *16*(1), 47–51.

Rogers, S., & Papanikolopulos, N. P. (2000). *Bicycle Counter*. *Minnesota Department of Transportation Office of Research & Strategic Services*. Minneapolis, Minnesota (USA).

Rojas-Rueda, D., de Nazelle, A., Tainio, M., & Nieuwenhuijsen, M. J. (2011). The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. *Bmj*, *343*(aug04 2), d4521–d4521. https://doi.org/10.1136/bmj.d4521

Romanillos, G. (2013). Huella ciclista de Madrid (Madrid cyclist track). Retrieved from www.huellaciclistademadrid.es

Romanillos, G. (2014). Analysing and mapping the cyclable city. A GPS-based analysis of the real and potential bicycle use in Madrid. In *15th International Conference on Information Technology in Landscape Architecture*.

Romanillos, G., Austwick, M. Z., Ettema, D., Kruijf, J. De, Romanillos, G., Austwick, M. Z., … Kruijf, J. De. (2015). Big Data and Cycling, *1647*(October). https://doi.org/10.1080/01441647.2015.1084067

Romanillos, G., Gómez-Moya, B., Zaltz-Austwick, M., & Lamíquiz-Daudén, P. J. (2018). The pulse of the cycling city: visualising Madrid bike share system GPS routes and cycling flow. *Journal of Maps*, *14*(1), 34–43. https://doi.org/10.1080/17445647.2018.1438932

Romanillos, G., & Zaltz Austwick, M. (2015). Madrid cycle track: visualizing the cyclable city. *Journal of Maps*, *12*(5), 1–9.

Romanillos, G., Zaltz Austwick, M., Ettema, D., & De Kruijf, J. (2016). Big data and cycling. *Transport Reviews*, *36*(1), 114–133.

Rondinella, G. (2015). *Considering cycling for commuting the role of mode familiarity: an exploration on the (circular) relation between cycling behaviours and attitudes toward cycling in Vitoria-Gasteiz, Spain*. Universidad Politécnica de Madrid. Retrieved from http://oa.upm.es/36379/1/Gianni_Rondinella.pdf

Rondinella, G., Fernandez-Heredia, A., & Monzón, A. (2012). Analysis of perceptions of utilitarian cycling by level of user experience. In *Transportation Research Board 91st Annual Meeting*.

Rybarczyk, G., & Wu, C. (2010). Bicycle facility planning using GIS and multi-criteria decision analysis. *Applied Geography*, *30*(2), 282–293. https://doi.org/10.1016/j.apgeog.2009.08.005

Ryus, P., Laustsen, K. M., Proulx, F. R., Schneider, R. J., & Hull, T. (2014). *Methods and Technologies for Pedestrian and Bicycle Volume Data Collection* (Vol. D). Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w205.pdf

Saghapour, T., Moridpour, S., & Thompson, R. G. (2017). Measuring cycling accessibility in metropolitan areas. *International Journal of Sustainable Transportation*, *11*(5), 381–394. https://doi.org/10.1080/15568318.2016.1262927

Salonen, M., & Toivonen, T. (2013). Modelling travel time in urban networks: Comparable measures for private car and public transport. *Journal of Transport Geography*, *31*, 143–153. https://doi.org/10.1016/j.jtrangeo.2013.06.011

Savage, N. (2010). Cycling through data. *Communications of the ACM*, *53*(9), 16–17. https://doi.org/10.1145/1810891.1810898

Schimek, P. (1997). *The dilemmas of bicycle planning*. Volpe Center.

Schneider, R., Patten, R., & Toole, J. (2005). Case Study Analysis of Pedestrian and Bicycle Data Collection in U.S. Communities. *Transportation Research Record: Journal of the Transportation Research Board*, *1939*(1), 77–90. https://doi.org/10.3141/1939-10

Schuessler, N., & Axhausen, K. W. (2009a). *Map-matching of GPS traces on high-resolution navigation networks using the Multiple Hypothesis Technique (MHT)*. Retrieved from http://www.baug.ethz.ch/ivt/ivt/vpl/publications/reports/ab568.pdf

Schuessler, N., & Axhausen, K. W. (2009b). Processing Raw Data from Global Positioning Systems Without Additional Information. *Transportation Research Record: Journal of the Transportation Research Board*, *2105*(1), 28–36. https://doi.org/10.3141/2105-04

Shaheen, S. a., Guzman, S., & Zhang, H. (2010). Bikesharing in Europe, the Americas, and Asia. *Transportation Research Record: Journal of the Transportation Research Board*, *2143*(1), 159–167. https://doi.org/10.3141/2143-20

Shen, L., & Stopher, P. R. (2014). Review of GPS Travel Survey and GPS Data-Processing Methods. *Transport Reviews*, *34*(3), 316–334. https://doi.org/10.1080/01441647.2014.903530

Smith, W. (2014). *Mobile interactive fitness technologies and the recreational experience of bicycling: A phenomenological exploration of the Strava community.*

Snizek, B., Sick Nielsen, T. A., & Skov-Petersen, H. (2013). Mapping bicyclists' experiences in Copenhagen. *Journal of Transport Geography*, *30*, 227–233. https://doi.org/10.1016/j.jtrangeo.2013.02.001

Sparkes, M. (2014). GPS big data: making cities safer for cyclists. *The Telegraph*. Retrieved from http://www.telegraph.co.uk/technology/news/10818956/GPS-big-data-making-cities-safer-for-cyclists.html

Stopher, P., Clifford, E., Zhang, J., & Fitzgerald, C. (2008). *Deducing mode and purpose from GPS data*.

Strava. (2014a). Does Strava have enough data to provide a meaningul dataset? Retrieved from http://metro.strava.com/thank-you/

Strava. (2014b). Strava Saturday heat map. Retrieved September 15, 2014, from http://www.strava.com/saturday-heatmap#0%7C12%7C3%7C30.50000%7C-40.80000

Strava Labs. (2014). Strava Labs. Retrieved September 15, 2014, from http://labs.strava.com/heatmap/#5/-110.69370/35.21986/blue/bike

Strava Metro. (2014). Strava Metro. Retrieved September 15, 2014, from www.metro.strava.com

Systems, D. T., & Lackner, B. (2013). Modeling Demand for Bicycle Sharing Systems – neighboring stations as a source for demand and a reason for structural breaks. In *TRB* (pp. 1–19).

Tilahun, N. Y., Levinson, D. M., & Krizek, K. J. (2007). Trails, lanes, or traffic: Valuing bicycle facilities with an adaptive stated preference survey. *Transportation Research Part A: Policy and Practice*, *41*(4), 287–301. https://doi.org/10.1016/j.tra.2006.09.007

Transport for London. (2015). *London Travel Report*. London. Retrieved from https://tfl.gov.uk/corporate/publications-and-reports/travel-in-london-reports

Turner, S. (1998). *Development of a methodology to estimate bicycle and pedestrian travel demand*. *College Station TX Texas*. Retrieved from http://www.worldcat.org/title/development-of-a-methodology-to-estimate-bicycle-and-pedestrian-travel-demand/oclc/40859970&referer=brief_results

Vlakveld, W. P., Twisk, D., Christoph, M., Boele, M., Sikkema, R., Remy, R., & Schwab, A. L. (2014). Speed choice and mental workload of elderly cyclists on e-bikes in simple and complex traffic situations: A field experiment. *Accident Analysis and Prevention*, *74*, 97–106. https://doi.org/10.1016/j.aap.2014.10.018

Vogel, P., Greiser, T., & Mattfeld, D. C. (2011). Understanding Bike-Sharing Systems using Data Mining: Exploring Activity Patterns. *Procedia - Social and Behavioral Sciences*, *20*, 514–523. https://doi.org/10.1016/j.sbspro.2011.08.058

Wamsley, K. (2014). *Optimal Power-based cycling pacing strategies for Strava Segments*. Kutztown University of Pennsylvania.

Wehner, M. (2014). Strava begins selling your data points, and no, you can't opt-out. *Tuaw*. Retrieved from http://www.tuaw.com/2014/05/23/strava-begins-selling-your-data-points-in-the-hopes-of-creating/

Wei, H., Huang, J., & Wang, J. (1997). Models for estimating traffic capacity on urban bicycle lanes. In *76th Annual Meeting of the Transportation Research Board, Washington, DC*.

Wergin, J., & Buehler, R. (2018). Where do Bikeshare Bikes Actually Go ? An Analysis of Capital Bikeshare Trips Using GPS Data. *Transportation Research Record*, (January).

Willis, D. P., Manaugh, K., & El-Geneidy, A. (2015). Cycling under influence: summarizing the influence of perceptions, attitudes, habits, and social environments on cycling for transportation. *International Journal of Sustainable Transportation*, *9*(8), 565–579. https://doi.org/10.1080/15568318.2013.827285

Witlox, F., & Tindermans, H. (2004). Evaluating bicycle-car transport mode competitiveness in an urban environment. An activity-based approach. *World Transport Policy & Practice*, *10*(4), 32–42. Retrieved from http://www.eco-logica.co.uk/pdf/wtpp10.4.pdf#page=32

Xu, C., Li, Q., Qu, Z., & Jin, S. (2015). Predicting Free Flow Speed and Crash Risk of Bicycle Traffic Flow Using Artificial Neural Network Models, *2015*.

Yang, C., & Mesbah, M. (2013). Route Choice Behaviour of Cyclists by Stated Preference and Revealed Preference. In *Australasian Transport Research Forum*. Brisbane, Australia. Retrieved from http://www.patrec.org/atrf.aspx Route

Zaltz Austwick, M., O'Brien, O., Strano, E., & Viana, M. (2013a). The Structure of Spatial Networks and Communities in Bicycle Sharing Systems. *PLoS ONE*, *8*(9). https://doi.org/10.1371/journal.pone.0074685

Zaltz Austwick, M., O'Brien, O., Strano, E., & Viana, M. (2013b). The structure of spatial networks and communities in bicycle sharing systems. *PloS One*, *8*(9), e74685. https://doi.org/10.1371/journal.pone.0074685